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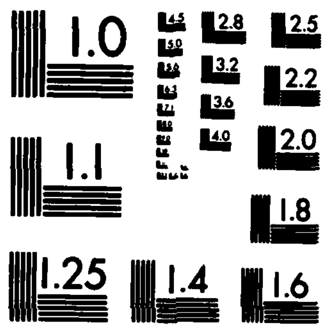

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IDA PAPER P-1762

CONTINUING ISSUES (FY 1983) CONCERNING MILITARY USE OF THE SPACE TRANSPORTATION SYSTEM

AD-A146 091

Reinald G. Finke
Charles J. Donlan
George W. Brady

December 1983

Prepared for
Office of the Under Secretary of Defense for Research and Engineering

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This study is a continuation of IDA studies of DoD concerns about the Space Transportation System (STS). Principal issues were the payload and cost of upper stages for delivery to geostationary orbit (GEO) from the Shuttle, and the possible trends to cost and operational efficiency of the Shuttle itself.

Regarding the GEO payload capabilities of different upper stages on the Shuttle, the study addressed the capability from VAFB to GEO of the

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Centaur, the size and costs of conventional "hybrid" integral-propulsion solid perigee stages to utilize efficiently an integral submultiple of the Shuttle cargo bay, the compatibility of apogee-insertion and evasive-maneuvering requirements in defining the thrust of the engine for the integral propulsion system, the performance improvements in allowing the integral propulsion system to grow to fill the orbiter's total capacity on a fixed-size solid perigee stage, and the performance into 65-deg or 8-deg-inclination 24-hr circular orbits in comparison with that in GEO.

Regarding the cost trends, the study addressed the potential cost to users if full cost recovery is adopted as the pricing policy after FY 1988, the relative costs of 1986 GEO delivery by expendable launch vehicles or the Shuttle with various upper stages, the comparison of actual experienced integration costs with 1979 Air Force predictions, the impact on the cost of the Shuttle for U.S. Government users from a change in commercial utilization, the projected improvements in Shuttle turnaround time, the potential advantages of nomad crews for VAFB launches of the Shuttle, and features and possible limitations of the Shuttle Processing Contract.

Finally, some new initiatives to enhance STS operations are described briefly.

IDA PAPER P-1762

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December 1983

INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION
1801 N. Beauregard Street, Alexandria, Virginia 22311

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Regarding the GEO payload capabilities of different upper stages on the Shuttle, the study addressed the capability from VAFB to GEO of the Centaur, the size and costs of conventional "hybrid" integral-propulsion solid perigee stages to utilize efficiently an integral submultiple of the Shuttle cargo bay, the compatibility of apogee-insertion and evasive-maneuvering requirements in defining the thrust of the engine for the integral propulsion system, the performance improvements in allowing the integral propulsion system to grow to fill the orbiter's total capacity on a fixed-size solid perigee stage, and the performance into 65-deg or 8-deg-inclination 24-hr circular orbits in comparison with that in GEO.

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Finally, some new initiatives to enhance STS operations are described briefly.

CONTENTS

ABBREVIATIONS

AKS	Apogee Kick Stage
APU	Auxiliary Power Unit
ASE	Airborne Support Equipment
BLS	Bureau of Labor Statistics
BOC	Base Operations Contractor
BRM	Baseline Reference Mission
C&F	Commercial and Foreign
CITE	Cargo Integration Test Equipment
CSD	Chemical Systems Division of United Technologies Corporation
ΔV	Velocity Increment
DoD	Department of Defense
ELV	Expendable Launch Vehicle
ET	External Tank
ETR	Eastern Test Range
FOS	Flight Operations Support
FY	Fiscal Year
G&C	Guidance and Control
GEO	Geostationary Orbit
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HAC	Hughes Aircraft Company
HB	High Bay
HEO	High Earth Orbit
HPM	High Performance Motor
IDA	Institute for Defense Analyses
IPS	Integral Propulsion System
IPSM	Improved Performance Solid Motor
I_{sp}	Specific Impulse
IRIS	Italian Research Interim Stage
IUS	Inertial (Interim) Upper Stage
IV&V	Independent Validation and Verification
JSC	Johnson Space Center

KSC	Kennedy Space Center
λ'	Mass Fraction (Ratio of Propellant Weight to Stage Weight)
LEO	Low Earth Orbit
LOS	Launch Operations Support
LRU	Line Replaceable Unit
LSA	Launch Services Agreement
MDAC	McDonnell Douglas Aircraft Co.
MLP	Mobile Launcher Platform
MM	Minuteman
MMB	Multimission Bus
MMU	Manned Maneuvering Unit
MSFC	Marshall Space Flight Center
M-X	M-X Peacekeeper
N_2O_4/MMH	Nitrogen Tetroxide/Mono Methyl Hydrazine propellants
NASA	National Aeronautics and Space Administration
O_2/H_2	Oxygen/Hydrogen propellants
OMS	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
OPF	Orbiter Processing Facility
OSC	Orbital Sciences Corporation
OTV	Orbital Transfer Vehicle
OV	Orbiter Vehicle
PAM	Propulsion Assist Module
PIC	Payload Integration Contractor
PIP	Payload Integration Plan
PL	Payload
Q_{max}	Maximum Dynamic Pressure
RAP	Responsibility Accounting Program
RCS	Reaction Control System
RFP	Request for Proposal
RL-10	Pratt and Whitney O_2/H_2 Rocket Engine
SAIL	Shuttle Avionics Integration Laboratory
SAMSO	Space and Missile Systems Organization
SD	Space Division
SMAB	Solid Motor Assembly Building
SOW	Statement of Work
SPC	Shuttle Processing Contract
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
STAG	Shuttle Turnaround Analysis Group
STAR	Shuttle Turnaround Assessment Report
STS	Space Transportation System

TBD	To Be Determined
TDRS	Tracking and Data Relay Satellite
TMS	Teleoperator Maneuvering System
TOS	Transfer Orbital Stage
TRW	Thompson Ramo Wooldridge
T/W	Thrust/Weight
VAB	Vehicle Assembly Building
VAFB	Vandenberg Air Force Base
VLS	Vandenberg Launch Site
WTR	Western Test Range

EXECUTIVE SUMMARY

This study* continues previous IDA studies and analysis efforts examining issues concerning military space activities involving the Space Transportation System (STS), i.e., the Space Shuttle and ancillary components. The objective was to collect information and conduct analyses that would allow a critique of NASA and DoD programs to increase the probability that the STS will meet its commitments in performing military missions. To be examined in particular (see the Appendix for the Task Order) were the payload capabilities into geostationary orbit (GEO) of emerging commercially-funded upper stages in comparison with Centaur, and the recent developments in refining the costs of operations with the STS. Principal results of the examination in these two areas are summarized in the following:

A. STS GEO PAYLOAD CAPABILITY

The Shuttle/Centaur launched from Vandenberg Air Force Base (VAFB) can deliver less payload into GEO than the combination can from Kennedy Space Center (KSC) because of the greater launch latitude of VAFB and launch azimuth constraints that prevent it from being launched due east. The minimum inclination achievable from VAFB is 56 deg; including consideration of some possible hazards of fallout of the external tank, the minimum inclination may be 70 deg. Summarized in the following table are (1) the parking orbit insertion capability of the Shuttle from both launch sites for two Solid Rocket Booster (SRB) options and (2) the payload capability to GEO of two Centaur/Shuttle combinations for similar conditions. The GEO payload of Centaur G (the short version) from these inclinations is greater than

*Performed for the Office of the Director (Offensive and Space Systems), OUSDRE.

that of G' (the long version) and would be about 7,700 lb or 4,000 lb, respectively, from the two inclinations. Assuming that the filament-wound SRB cases would produce a 5,500-lb increase in Shuttle payload, the GEO payload would grow to about 8,800 lb (now Centaur G') and 5,500 lb (Centaur G) from the 56-deg and 70-deg inclination parking orbits, respectively.

Site	Orbital Inclination, deg	SRB* Option	Cargo Bay Payload, lb	Payload to GEO, lb	
				Centaur G	Centaur G'
ETR	28.5	A B	65,000 65,000	10,600 10,600	14.000 14,000
VAFB	56	A B	53,000 58,500	7,700 8,200	7,100 8,800
VAFB	70	A B	44,500 50,000	4,000 5,500	3,300 4,800

*A = Lightweight SRB's
B = Filament-wound SRB's.

Conventional "hybrid" integral propulsion, as treated here, involves a simple spinning solid-propellant-rocket stage, such as the PAM-D, to provide all of the perigee-kick ΔV for injection into a geosynchronous transfer orbit, and a liquid-rocket propulsion system built into the geostationary spacecraft to supply the apogee ΔV into GEO. To avoid unnecessary duplication of expensive guidance and control (G&C) systems in a separate stage, the G&C of the spacecraft would be used to control the built-in propulsion system, and the attitude reference and rotation of the spinning solid would be provided by systems aboard the Shuttle orbiter. Alternatively, a three-axis-stabilized solid perigee stage (e.g., the Transfer Orbital Stage, or TOS, derived from the IUS SRM-1) could use the guidance commands from the spacecraft transmitted across the structural interface.

The particular GEO perigee stage, that, with transfer-orbit payload and ASE, would use all the 65,000-lb Shuttle payload capability, would be about one-and-a-half times as heavy as the IUS SRM-1; scaled from that stage (actually from the TOS) it would deliver about 20,500 lb into the transfer orbit and, with an integral propulsion system having characteristics similar to the Marquardt R-40 engine, would deliver a net payload of about 10,350 lb into GEO. The TOS is too heavy for two-at-a-time launch on the Shuttle but with offloading of 30 percent of its propellant would fit half the Shuttle's payload capacity; each of such a pair would deliver about 8,700 lb to transfer orbit and, with integral propulsion similar to that above, about 4,400 lb net to GEO. (A spinning version of the IUS SRM-1, as to be used with INTELSAT VI, would have a lower inert stage weight than TOS and slightly more payload.) The PAM-DII is sized almost exactly for four-at-a-time launch, giving about 4,000 lb each in transfer orbit, and, with integral propulsion, a net GEO payload of about 2,000 lb for each of the four.

In the tradeoff in selecting the thrust level for the integral liquid propulsion system that provides the GEO-insertion ΔV, high engine weight at short burn times is to be balanced against high g-loss-propellant weight at long burn times. A minimum sum of engine weight and g-loss-propellant weight of about 54 lb for a 5000-lb example satellite is obtained for a burn time of about 17 minutes (about 1,300-lb thrust), with the sum of the weights remaining at or below 80 lb for thrust levels between about 700 lb and 2,800 lb. In this thrust range, the non-impulsive ΔV requirement for an example maneuver of 75 nmi in 30 minutes exceeds the ideal impulsive ΔV requirement by only about one percent. The 700-lb-thrust Marquardt R-40 engine therefore appears to be a good candidate for satellites in the 5000-lb class.

While the conventional "hybrid" integral propulsion system is typified by the communication-satellite designs of Hughes, TRW advocates another form of IPS, a "unitary" form. In the unitary IPS concept, the liquid propulsion system within the spacecraft provides the ΔVs for both the injection in the GEO transfer orbit and the apogee circularization, eliminating the solid perigee stage as an element. Alternatively, the distinction between the two concepts can be made that the solid perigee stage provides either <u>all</u> or <u>none</u> of the ΔV for injection in the GEO transfer orbit. The hybrid system sized to occupy all the Shuttle's 57,000-lb separation weight capacity (65,000 lb gross less 8000 lb of ASE) is calculated above to carry a net payload of about 10,350 lb into GEO; similar calculations with the unitary system indicate a net GEO payload of about 9,600 lb. It is of interest to determine the effect on the net GEO payload of varying the size of the solid perigee stage between the extremes for delivery of all the GEO-transfer perigee ΔV and none of it.

The analysis here indicates that there exists an optimum combination of solid perigee stage and IPS between the extremes exemplified by the conventional "hybrid" concept of Hughes and the "unitary" concept of TRW. The optimum sized solid stage, employed in an "overloaded" mode to use all the Shuttle's maximum-separation-weight capability, is about 14 percent larger than the IUS SRM-1 (typified by the TOS). This optimum combination, however, would deliver only about 20 lb more GEO payload than an overloaded TOS; the small payload advantage would hardly justify the additional development costs of this optimized stage over the IUS SRM-1 (or TOS). The TOS, overloaded with IPS and payload to add up to a 57,000-lb separation weight, is calculated to deliver about 10,600 lb (net) to GEO.

From a Shuttle parking orbit of 36.5-deg inclination (for which NASA projects the same Shuttle payload as 28.5-deg inclination), the GEO payload weight could be delivered to either an 8-deg or a 65-deg-inclination 24-hour orbit with a common-design propulsion system.

If the cost of IPS is indeed as low as estimated by Hughes and TRW, and evidenced by many commercial communications-satellite programs and by the Convair company-funded Spacecraft Maneuver Module, IPS should be preferable to the like-performance Centaur G for any spacecraft buy of more than one unit.

B. STS COSTS AND OPERATIONS

NASA has extrapolated the Shuttle's operations cost estimates generated for the establishment of the FY 1986-1988 pricing policy through FY 1994 for two traffic models, one with a plateau at 24 per year from FY 1988 on and a second that continues to grow to a higher plateau at 40 per year in

FY 1991 and thereafter. The familiar average cost values for FY 1986-1988 for this costing exercise are (in FY 1975 dollars per flight) \$29.8M for "Materials and Services" costs, \$38.0M for "out-of-pocket" costs, and \$55.7M for total costs. The "Materials and Services" costs represent the agreed charge to DoD (with the "Quid pro Quo" exchange of VAFB services for non-DoD users for KSC services for DoD users), and the \$38.0M is the charge to commercial and foreign (C&F) users, representing a sometimes-called subsidy of \$17.7M from the total costs. The extrapolation of these values to a representative future year of FY 1993 indicates that, for the maximum of 24 flights per year, the "Materials and Services" costs would become (still in FY 1975 dollars) \$23.8M and the total costs, \$46.4M. While there has been no agreement on DoD charges after FY 1988, the charges then to commercial and foreign (C&F) users currently are expected to grow to a full-cost-recovery policy. In the latter case, the new policy would result in an increase of about 22 percent in price from the FY 1986-1988 charges to C&F users. If the 40-flight-per-year rate comes about, however, the FY 1993 "Materials and Services" costs would decline to \$19.5M and the total costs would decline to \$33.8M, the latter representing an 11 percent reduction in full-cost-recovery charges from the "subsidized" FY 1986-1988 "out-of-pocket" charges.

An updated comparison of the costs of an FY 1986 launch of payloads into GEO by expendable launch vehicles (ELVs) and the Shuttle with various upper stages has been made. The new integral-propulsion-system concepts for the Shuttle are added to a revision of last year's comparison. The present comparison still indicates that all ELVs (except Ariane 4) and the Shuttle/IUS are significantly more expensive than Shuttle-based competitors, that Ariane 4 is competitive only if its price can be kept the same as its lower-payload progenitors, and that the Centaur shows the greatest promise of all the standardized upper stages. However, the estimates for the various versions of integral propulsion with different perigee kick stages are quite competitive with those for the Centaur in specific delivery costs and show lower launch costs for less-than-full-Centaur payloads.

In 1979, the Air Force Space Division (then called SAMSO) conducted a study of payload integration costs for an IUS-class spacecraft. Since then a Tracking and Data Relay Satellite (TDRS) with its IUS has been successfully launched from the Shuttle. Further, several smaller Delta-class satellites have also flown on the Shuttle. It is of interest to compare the predictions with experience. The actual total launch-related services costs for the TDRS-A (\$17.7M 1983 dollars) are about 40 percent lower than the corresponding amount from the USAF study (\$24.7M). The integration-cost part of the total for TDRS-A is \$11.5M (actual), and the charges for TDRS-B and -C drop to 37 percent and 27 percent, respectively, versus an AF prediction of a reduction to 40 percent for subsequent flights of the same payload. For the Delta-class payloads, the total costs of integration and optional services were about \$1.4M.

Since the cost of an individual Shuttle launch is expected to be less if the flight rate is greater, a change in the number of C&F users should lead to an inverse change in the cost of the basic U.S. government flight program. The analysis here, based on learning-curve cost dependences only, indicates that if an extra Shuttle flight in the FY 1986-1988 period beyond expectations is sold to a C&F user for the established price, the difference between the cost of an additional ET and SRBs and the price paid for them based on the expected traffic rate would give the U.S. Government a "profit" of about \$1.5M. If 20 Shuttle flights with ELV-compatible payloads in the FY 1986-1988 period are lost to ELVs, the average cost of the remaining ETs and SRBs will increase, causing a calculated total increase in cost to the U.S. Government of about \$21.8M spread over the three-year period, an average increase of about \$1.1M for each Shuttle flight. (For full cost recovery after FY 1988, the U.S. Government could gain a cost savings of the order of \$19M for each non-Government flight.)

A NASA/KSC review last year of Shuttle turnaround operations projections indicated that a group with greater hardware/operations orientation should be convened to upgrade the assessment of turnaround reduction. New approaches taken by this group were in two principal directions: (1) measuring operating limits more exactly so that unnecessary conservatism in servicing and safety precautions could be identified and eliminated, and (2) reconfiguring servicing-facility elements and Shuttle components to facilitate maintenance and checkout operations. With the changes in procedures and hardware that were identified, the turnaround-reduction group projected that the turnaround time from landing to launch could be reduced to 22 three-shift working days by the time of STS-21, with an associated investment in hardware changes of less than $2M. With this turnaround time and a five-day work week, the fleet of four orbiters should be able to achieve a maximum flight rate of about 37 per year, with a surge capability to about 45 per year with an increase in work week from five to six days. These projections shift the focus of attention from launch servicing to other choke points, such as ET production, that could limit the achievable Shuttle flight rate.

The increment in cost of overall Shuttle launch operations for the relatively infrequent launches from VAFB could be decreased by reducing the duplication of crews at the two sites; a significant component of the crew normally based at KSC could be transferred temporarily to VAFB to effect a launch. Such a procedure was used successfully for non-simultaneous Delta operations at WTR and ETR. Part of the 200-odd people stationed at Cape Canaveral were moved to VAFB for a launch to supplement a skeleton crew of only about 20 people there. Procedures developed for Delta should be useful to the Shuttle Processing Contractor for reducing significantly Shuttle operations costs at VAFB.

The Shuttle Processing Contract is intended to consolidate the management and conduct of Shuttle launch operations at both KSC and VAFB under one contractor. The Request for Proposal (RFP) includes a formulation of proposed practices to bring about a reduction in Shuttle launch costs and an increase in the number of launches over the Mission Model. Some of the formulated practices appear to need further definition to remove uncertainties in implementation. A principal question concerns the structure of the incentive fee formula. A complication in determining the fee earned for one more mission beyond the Mission Model can be removed by a minor modification of a definition. More importantly, the published formulation of the incentive fee, taken with a fee limit of 15 percent of the estimated costs for a period of performance, can lead to a situation in which the contractor can earn his maximum fee for a number of launches less than that projected by the Mission Model. To rectify this undesirable situation, the contracting agency can either set the parameters in the formula low, which would have the effect of reducing the contractor's possible fee for early years, or allow the parameters in the formula to vary with the number of flights in the Mission Model, which, in the lack of a preassigned variability, would require recurrent revision of the contract. Selection of the preferred option will depend on experience gained in the transition period.

The report concludes with a brief description of some new programs that may have some effect on space transportation, i.e., the Space Station, tethers for subsatellites, and the Teleoperator Maneuvering System.

I. INTRODUCTION

The STS has now completed a number of operational launches, including successful deployment of upper stages. Two orbiters are operational and delivery of a third has just been made. New commercially-funded upper-stage concepts are emerging to expand the flexibility of the STS. A pricing policy for Shuttle flights has been established for the FY 1986-1988 time period, supporting the ability of the Shuttle to compete successfully with expendable launch vehicles. A Shuttle Processing Contractor has been chosen to consolidate the management and conduct of Shuttle launch operations at both KSC and VAFB under one contractor to improve efficiency and reduce costs. External-tank weight reduction from the lightweight tank program has turned out to be better than projected, and development of a new lightweight filament-wound case for the solid-rocket boosters has been initiated. The STS advancement seems to be comfortably exceeding expectations. Questions remain, however, regarding the continuation of this momentum in successfully implementing these unprecedented programs to achieve the planned STS payload capability, in capitalizing fully on experience to improve operational efficiency, and in recognizing and correcting limitations in meeting evolving user requirements.

Principal questions addressed in this report concern the geostationary-orbit (GEO) payload capability of different upper stages with the Shuttle, and the improvements in understanding the costs and the operational efficiency of the Shuttle. Specific questions in each area are the following:

A. STS GEO PAYLOAD CAPABILITY

1. What is the GEO payload capability from VAFB of the Centaur within the Shuttle constraints in payload (including airborne support equipment) into parking orbits of different inclination?

2. What GEO payload can be delivered by conventional "hybrid" integral propulsion systems (IPSs), and what are the solid perigee-kick motor sizes that are required, within an integral fraction, i.e., 1/4, 1/3, 1/2, and 1/1, of the Orbiter's cargo-bay weight capacity for a 28.5-deg-inclination orbit from KSC?
3. What are the relative GEO delivery costs of these solid perigee-kick stages with respect to those of Centaur?
4. What size rocket engine should be used by the spacecraft's integral liquid propulsion system to satisfy demands for geostationary insertion and evasive maneuvering?
5. What is the size of the solid perigee-kick stage that gives the maximum GEO payload within the limitations of the Shuttle lift capability?
6. What is the relative performance of "hybrid" and "unitary" IPS?
7. What is the payload performance into 65-deg-inclination or 8-deg-inclination 24-hr circular orbits with respect to that in GEO?

B. STS COSTS AND OPERATIONS

1. What might be the cost to Shuttle users if full cost recovery (rather than "out-of-pocket" costs) is adopted as the pricing policy after FY 1988?
2. What is the relation between the cost of GEO delivery by various expendable launch vehicles and by the Shuttle with various upper stages, including the new IPS concepts?
3. How do actual Shuttle integration costs for different classes of payloads compare with predictions?
4. What would be the change in cost of the Shuttle to government users if there were a change in the number of commercial or foreign flights?
5. What turnaround time between Shuttle flights is NASA/KSC now aiming to achieve?

6. What reduction in VAFB launch crew might be obtained by temporarily transferring crews normally based at KSC to VAFB to accomplish the infrequent launch there?

7. What are the potential features and limitations of the Shuttle Processing Contract in consolidating KSC and VAFB launch operations under one contract?

Finally, the report discusses briefly some new initiatives, e.g., the Space Station, that may have some impact on the operations of the STS.

The cutoff date for information included in this paper was December 7, 1983.

II. SPACE TRANSPORTATION SUPPLEMENTS--PERFORMANCE FOR GEOSTATIONARY MISSIONS

IDA, 1982, Chapter II, discusses performance of the Space Shuttle with a variety of upper stages to place payloads into geostationary orbit. Program developments during early 1983 resulted in an agreement between NASA and the USAF to develop two versions of the cryogenic-propellant Centaur for missions beyond the capability of the IUS; these are designated Centaur G and G'. In addition, new configurations based on the IUS SRM-1 and the IPS or integral propulsion system have emerged. This section presents the results of further analysis of the Centaur performance and a new analysis of the integral propulsion systems.

A. CENTAUR PERFORMANCE TO GEO FOR VARIOUS PARKING ORBIT INCLINATIONS

The two Centaur vehicles for use with the Space Shuttle are derivatives of the Centaur D-1 which has flown successfully for a number of years as the upper stage for the Atlas expendable launch vehicle. Advantage is taken of the 15-ft diameter of the Shuttle's cargo bay to increase the diameter of the LH_2 propellant tank to 14.2 ft. The G and G' versions differ primarily in length, being 19.5 and 26.5 ft, respectively. Fig. II-1 shows the general arrangement, and the following Table II-1 presents weight and related characteristics.

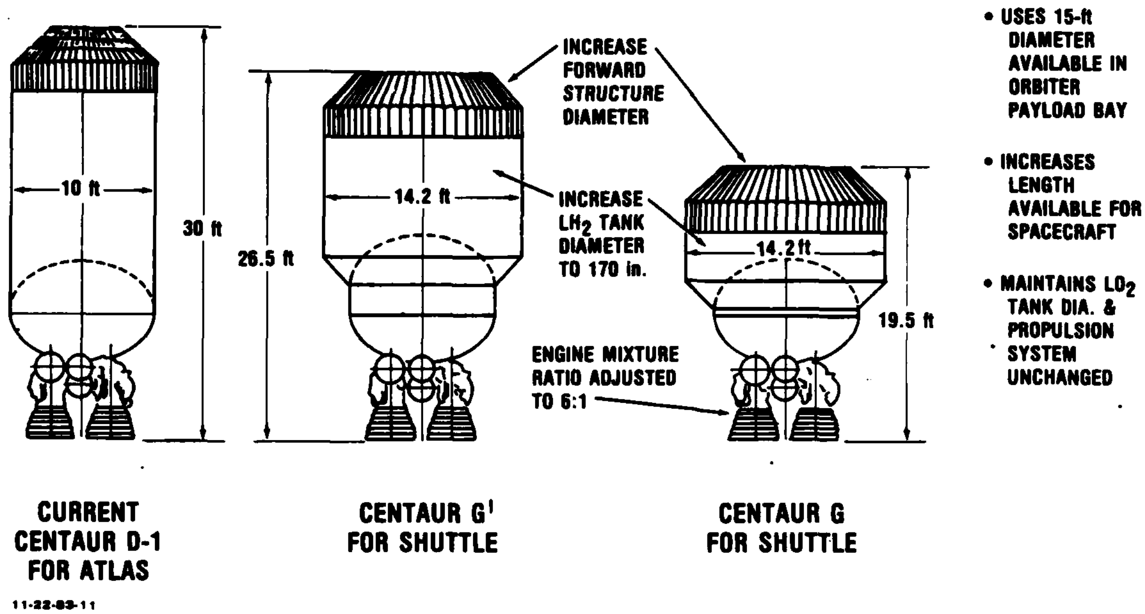


FIGURE II-1. Shuttle/Centaur is a minimum modification to current Centaur (courtesy General Dynamics/Convair)

TABLE II-1. CHARACTERISTICS OF CENTAURS G AND G'

	Centaur G	Centaur G'
Diameter of LH_2 Tank - ft	14.2	14.2
Diameter of LO_2 Tank - ft	10.0	10.0
Overall Length - ft	19.5	26.5
Weights - lb		
Tank Dry	5,775	6,091
Residual Propellant	431	600
Residual N_2H_4	92	92
Residual He	17	24
Residual Ice	17	17
Jettison Weight	6,332	6,824
Expendable Propellant	29,707	35,832*
Expendable N_2H_4	250	250
Expendable He	4	3
Centaur Tanked Weight	36,293	42,908
Spacecraft	10,676	14,061
ASE	7,462	8,031
Cargo Weight	54,431	65,000
Propulsion	2 RL-10	2 RL-10
Mixture Ratio (O_2/H_2)	6.0	5.0
I_{sp} (sec)	440	446

*Offloaded tank to maintain 65,000-lb weight; if fully loaded, propellant weight increases to 45,400 lb.

The following discussion concentrates on the performance of the two Centaur/Shuttle combinations into geostationary orbit (GEO) from KSC and VAFB. In IDA, 1982 the payload to GEO when launched due east (28.5 deg) from KSC is specified as:

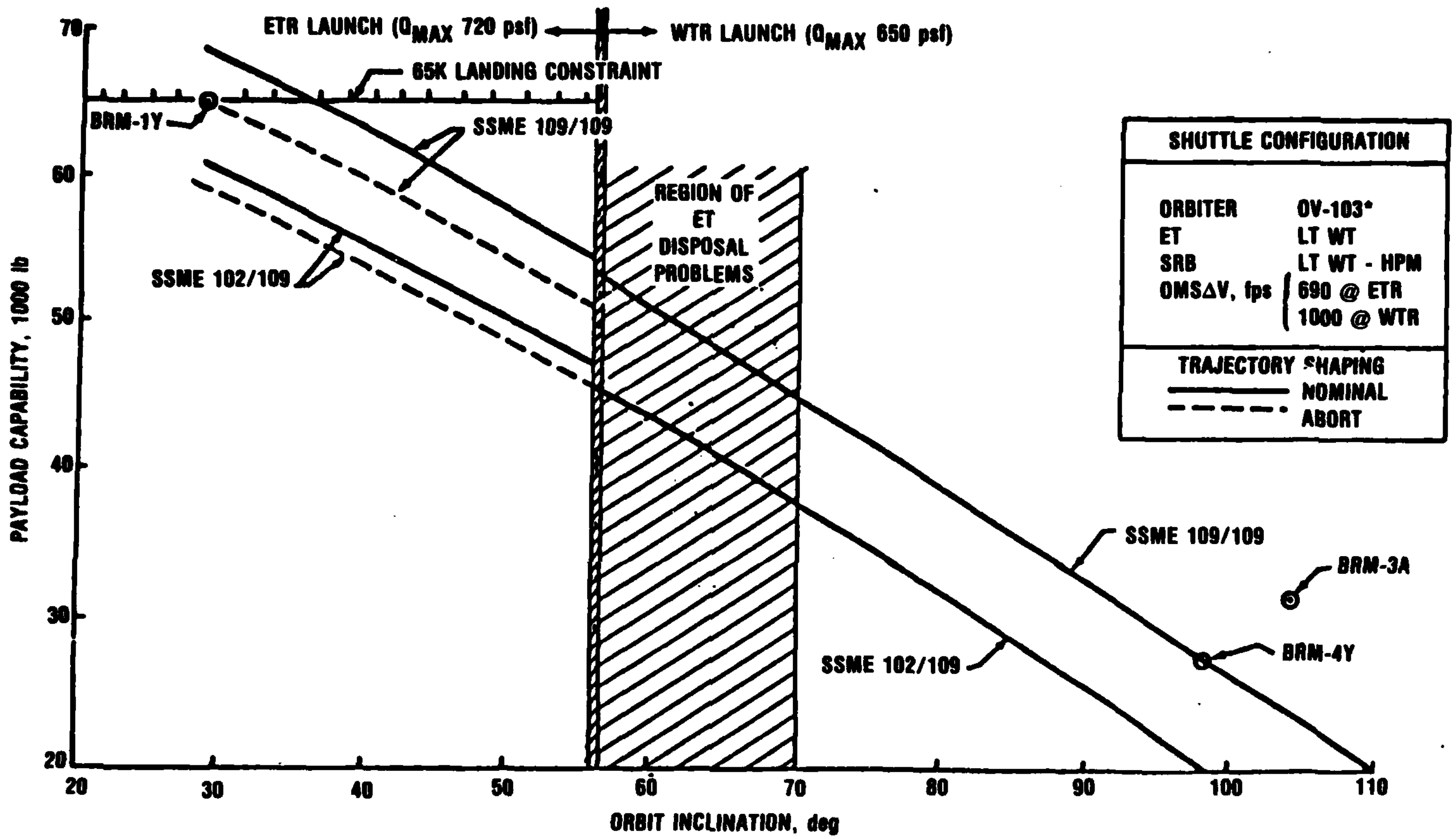
Centaur G	10,600 lb
Centaur G'	14,000 lb

The payload capability to GEO when launched in a southeasterly direction from VAFB (34.5-deg latitude) depends on the azimuth selected and the cargo bay capability of the Shuttle itself. Figure II-2, taken from JSC, 1983, shows the variation with orbital inclination. Pertinent payload values for the basic Shuttle—OV-103, 109/109 SSME, lightweight external tank, lightweight (but not composite case) HPM SRBs—are as follows:

Orbital Inclination, deg	Cargo Bay Payload, lb
28.5	65,000
56	53,000
65	47,500
70	44,500

The payload to GEO from a 160-nmi parking orbit using the above data is given below and plotted in Fig. II-3.

Orbital Inclination, degrees	Spacecraft Weight (including S/C ASE), lb	
	G	G'
28.5	10,600	14,000
56	7,695	7,070
65	5,200	4,600
70	3,955	3,335



*Based on projected weight JSC-09095-71 (April 1983)

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FIGURE II-2. Space Shuttle payload deployment capability versus inclination (crew/days 2M/1D, orbit altitude 150 nmi) (from JSC, 1983)

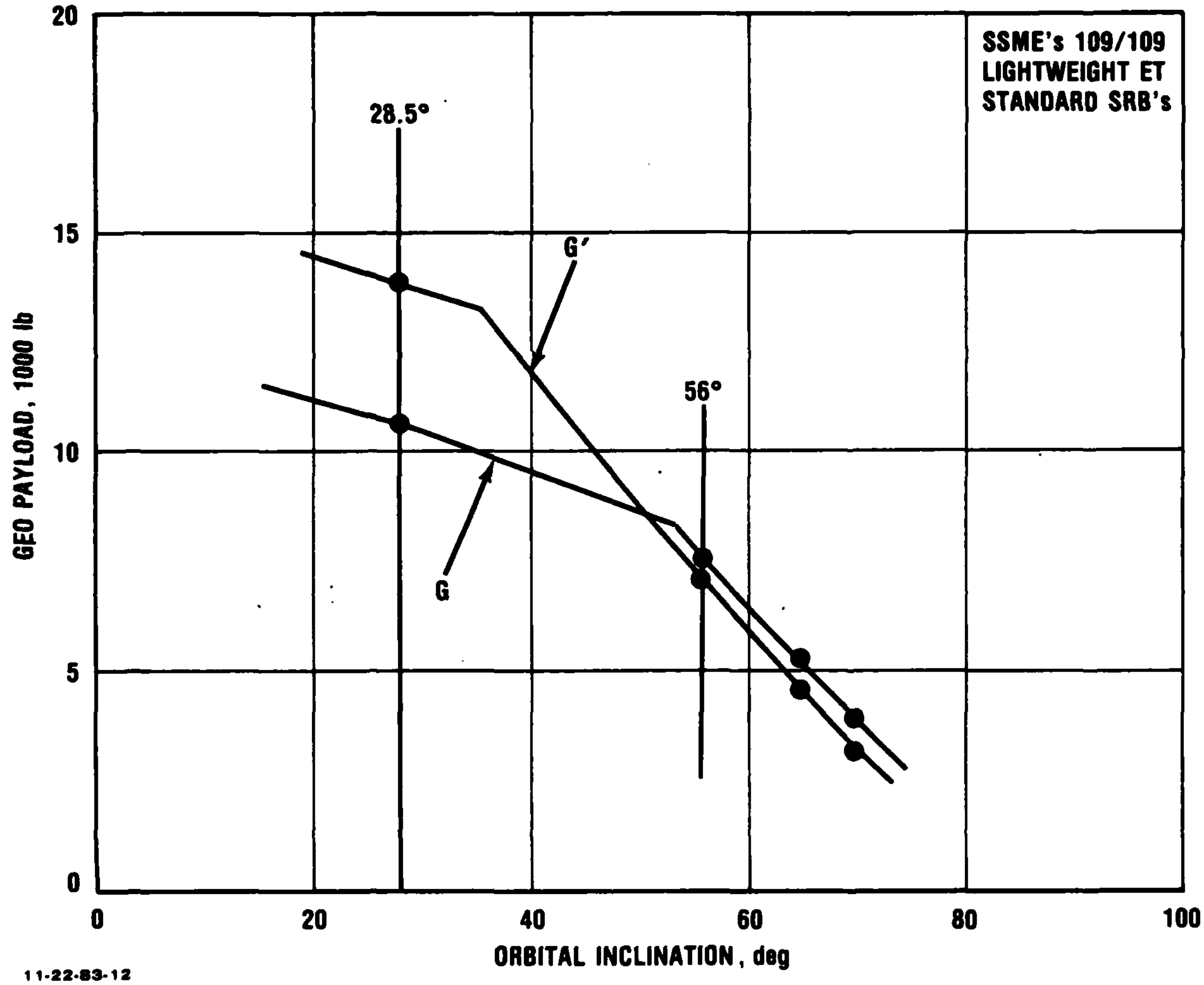


FIGURE II-3. Centaur G' payload to GEO versus orbital inclination (STS in basic 65K configuration)

The reason that the Centaur G outperforms the G' at 56 deg and beyond is that its jettison weight is approximately 500 lb less and also its ASE is about 550 lb lighter, both factors permitting more propellant to be carried.

Although the GEO payloads for the Centaurs in the Shuttle in its standard configuration are quite substantial, it is of interest to determine how much improvement is possible if the composite-case SRBs are used in place of the steel-case SRBs. NASA data show an increase in STS capability of 5500 lb up to the 65,000-lb STS maximum. For the 56-deg inclination this increase gives a 58,500-lb Shuttle capability which can be fully utilized by the Centaur G' in carrying more LH_2/LO_2 propellants; however, the increase in propellant loading for the Centaur G is limited by tank volume. Hence the incremental payload improvement for the Centaur G is only about 500 lb. The following table shows the GEO payload capability in 56- and 70-deg parking orbits for launches from VAFB for both Centaurs:

Inclination,	Payload	
degrees	G	G'
56	8,190	8,780
70	5,520	4,770

From the above payload numbers, it would be advantageous to utilize the 56-deg inclination if possible. Figure II-4, which is reproduced from IDA, 1978, and Fig. II-2 both state that there may be a problem in the disposal of the External Tank (ET) for inclinations between 56 deg and 70 deg. (Lower inclinations than 56 deg are not practicable because the SRB cases will impact too close to the Baja California Peninsula.) Figure II-5 is a plot of the orbital tracks and shows that for either inclination whatever fragments of the ET that survive reentry will land in the Indian Ocean. Hence, if the USAF or NASA should need to launch GEO payloads from VAFB, quite substantial payloads can be carried with the Centaur G, particularly if the 56-deg parking orbit is used.

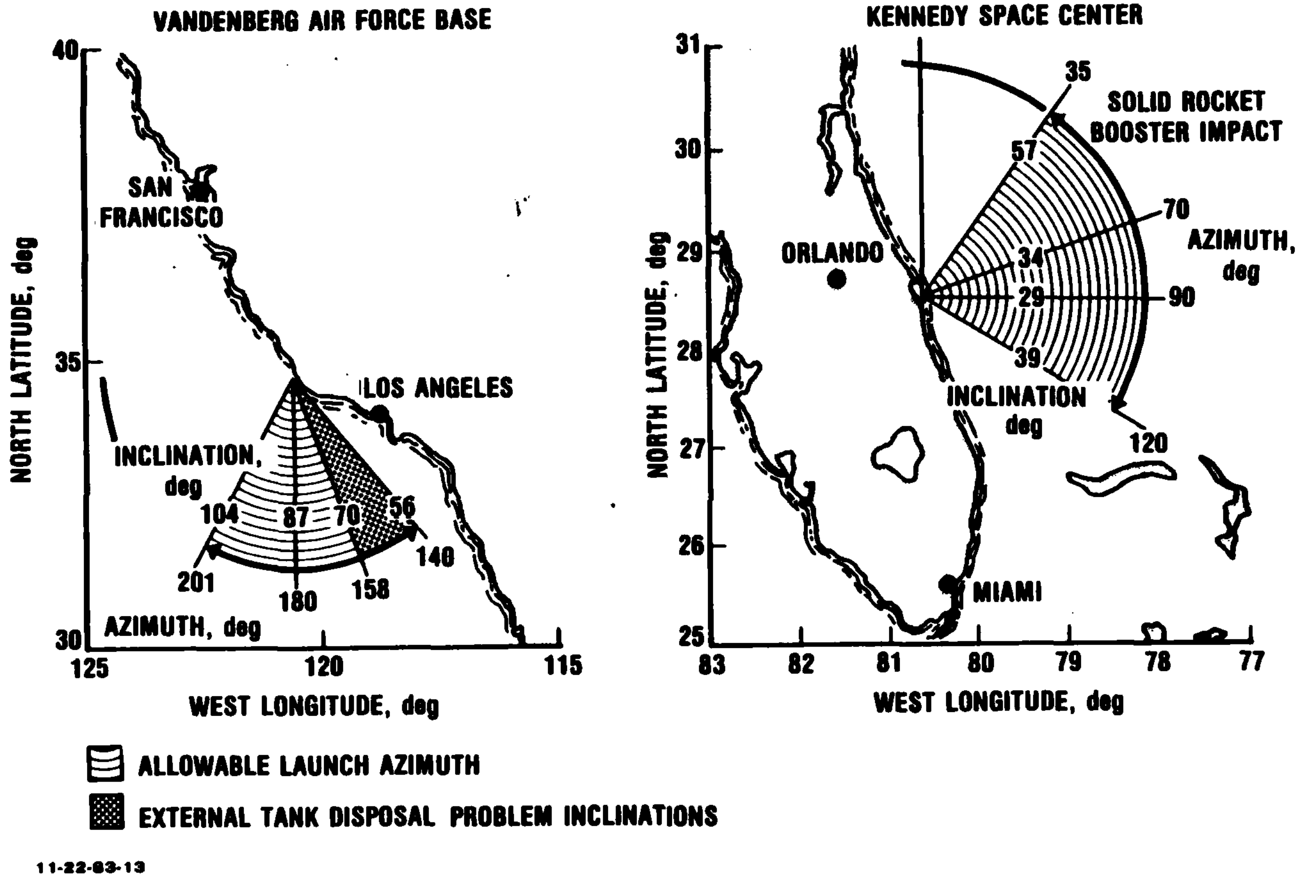


FIGURE II-4. Practical launch azimuth and inclination limits from VAFB and KSC (from IDA, 1978)

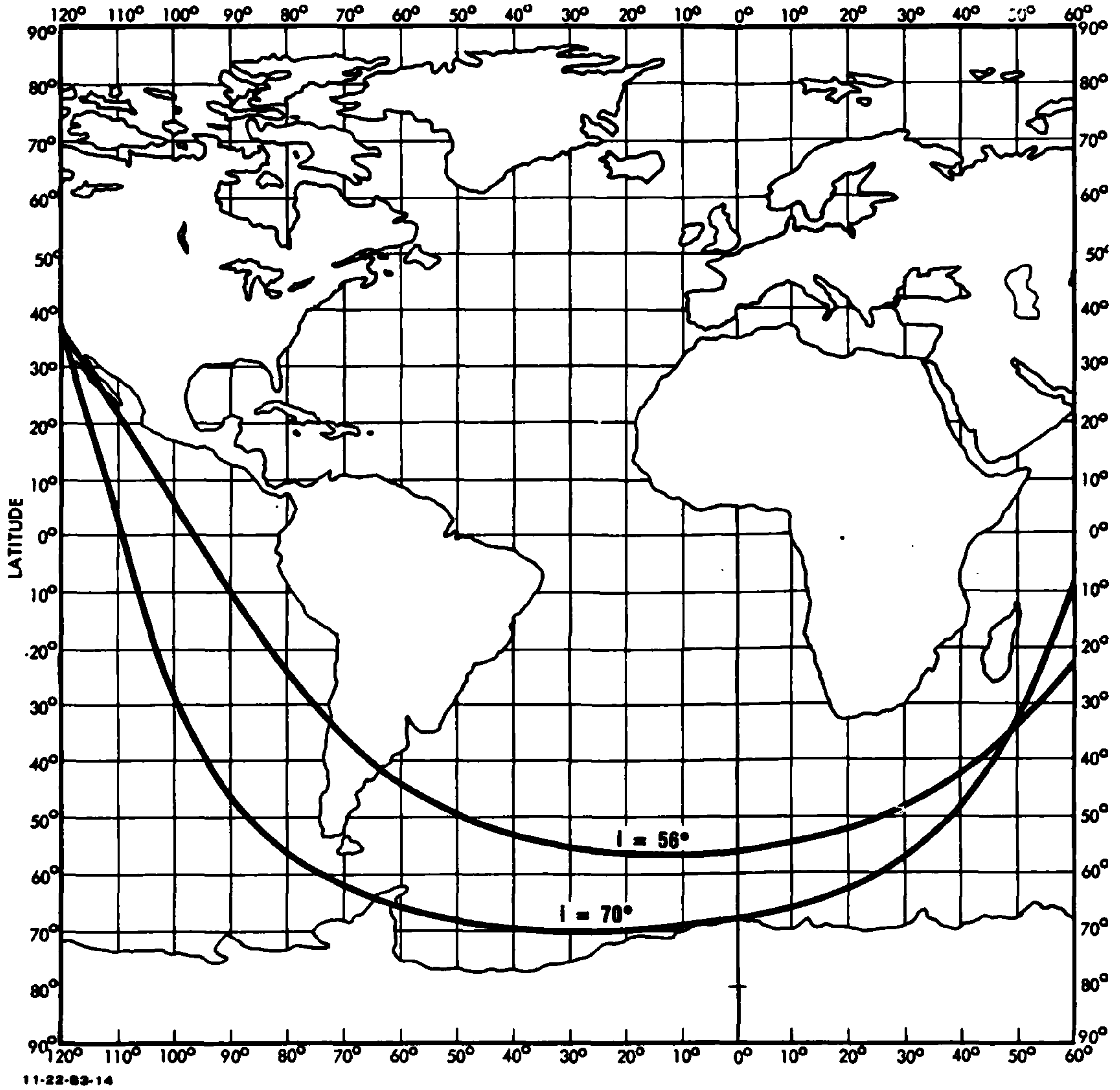


FIGURE II-5. External-tank disposal trajectories from VAFB

B. CURRENT INTEGRAL-PROPULSION CAPABILITIES

1. Introduction

"Integral Propulsion" is a term that has been used to denote incorporation of an apogee-kick propulsion system in a (generally) geostationary spacecraft to avoid unnecessary duplication of guidance and control systems in a separate stage. In the "hybrid" system conventionally used, the apogee-kick propulsion system uses liquid propellants, while the perigee kick is provided by a simple spinning solid rocket motor that has its attitude reference and rotation provided by systems aboard the Shuttle Orbiter.

A case for such an integral propulsion system in comparison with "standard upper stages," i.e., the IUS, and by implication the Centaur, has been made in HAC, 1983. It is of interest here to identify the principal defining issues in the use of this principal current version of integral propulsion and to quantify its potential characteristics and propulsion requirements.

The principal questions regarding conventional "hybrid" integral propulsion addressed in this section are the following:

1. What is the GEO payload that can be delivered, and what are the solid perigee-kick motor sizes that are required within an integral fraction, i.e., 1/4, 1/3, 1/2, and 1/1, of the Orbiter's cargo-bay weight capacity?
2. What are the relative delivery costs of these stages with respect to those of the Centaur?
3. What size rocket engine should be used by the spacecraft's integral liquid propulsion system to satisfy demands for geostationary insertion or evasive maneuvering?

2. Subdivision of Shuttle Lift Capability

The leading existing or proposed spinning solid stages to be launched from the Orbiter to provide the perigee-kick velocity increment are the PAM-D, PAM-DII, PAM-A, and a spinning version of the first-stage motor of the IUS (IUS SRM-1) for the INTELSAT VI satellite (the IUS SRM-1 is also to be used in the 3-axis-stabilized Transfer Orbital Stage, or TOS). Characteristics of these stages and some others are given in Table II-2. The calculated data in the last column are discussed at the end of this section.

TABLE II-2. CHARACTERISTICS OF SOLID PERIGEE STAGE CANDIDATES

Stage	Effective Propellant Weight (lb)	Stage Mass Fraction	Effective I_{sp} (sec)	Fraction of Shuttle Payload
IRIS	3,447	0.871	292.9	0.125
PAM-D	4,431	0.907	284.5	0.153
IUS SRM-2 (motor data)	6,037	0.914	302.5	0.220
PAM-DII	7,225	0.882	279.0	0.249
PAM-A	7,640	0.896	274.3	0.261
MM 2	14,313	0.903	280.3	0.467
M-X 3	16,650	0.916	306.5	0.562
TOS	21,404	0.892	295.0	0.687

To make the most efficient use of the Shuttle's lift capacity, the total weight of a stage plus its transfer-orbit payload plus ASE* should be such that an exact integral number of these assemblies will add up just to the 65,000-lb total payload capability into a 160-nmi, 28.5-deg parking orbit. (To simplify the analysis we assume that the density of an assembly can be adjusted by appropriate spacecraft design so that its submultiple share of the cargo-bay volume is not exceeded, i.e., that the average density is no less than about 6 lb/ft^3.)

*ASE: Airborne Support Equipment, i.e., cradle and interface equipment in Orbiter.

The observed variation of the projected weight of ASE with gross initial weight of stage plus transfer-orbit payload for values for a number of stages is shown in Fig. II-6. From the curve in the figure, the ASE weight for total weights equaling integral subdivisions of the Shuttle's weight-lifting capacity can be interpolated, to yield the remaining gross weight of the stage and payload in each case. The results are listed in Table II-3.

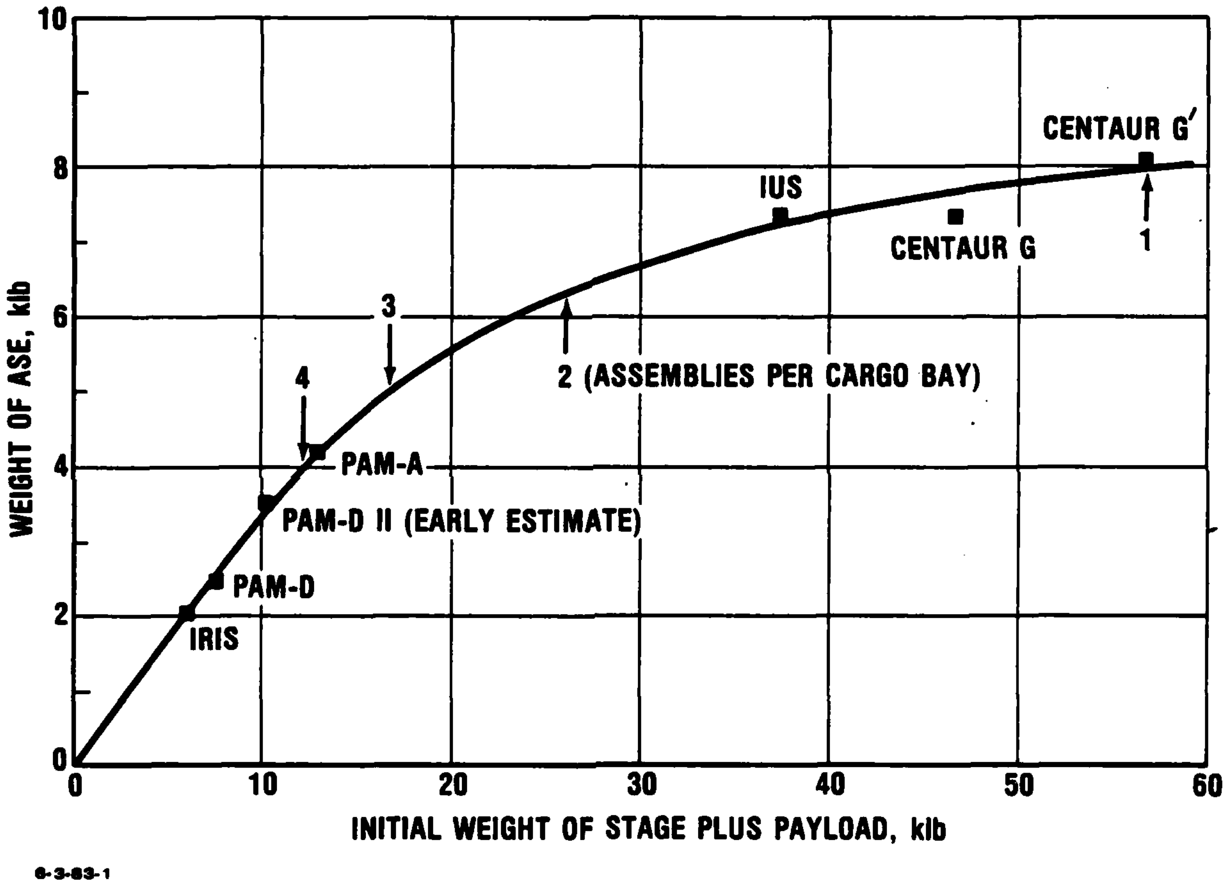


FIGURE II-6. Variation of ASE Weight with Weight Carried

The payload injected into the geostationary transfer orbit (160 nmi by 19,323 nmi, 26.2 deg) can be derived from assumed properties of the scaled perigee stage: mass fraction (propellant weight divided by stage weight) of 0.892 and specific impulse of 295 sec, values typical of the TOS version of the IUS SRM-1.

The final net payload inserted into GEO by the integral propulsion is derived from assumed properties of the built-in propulsion system: propellants of N_2O_4/MMH, mass fraction of 0.92, and an I_{sp} of 300 sec typical of the Marquardt R-40 engine, i.e., the larger RCS (Reaction Control System) engine of the Shuttle Orbiter. An increase in the I_{sp} by 10 sec (to 310 sec) would increase the GEO payload by about 2.3 percent. (Impulsive delivery of the ΔVs is assumed; the consideration of gravity losses for extended burn times is postponed to later discussion.)

The results of these simplified calculations for different integral values, 1, 2, 3, and 4, for the subdivision of the total Shuttle payload are given in Table II-3.

TABLE II-3. WEIGHTS (lb) OF CONCEPTUAL SCALED STAGES AND PAYLOADS FOR SUBMULTIPLE N OF SHUTTLE PAYLOAD

N (per cargo bay)	ASE+gross	ASE	Gross	Perigee Stage Propellant	Transfer-Orbit Payload	GEO Payload
1	65,000	8000	57,000	32,580	20,490	10,350
2	32,500	6300	26,200	14,970	9,420	4,760
3	21,670	5000	16,670	9,530	5,990	3,030
4	16,250	4000	12,250	7,000	4,400	2,220

The largest GEO payload, about 10,350 lb*, is in the class of the Centaur G and G', 10,600 and 14,000 lb, respectively. It requires, however, a perigee-stage propellant weight about one-and-one-half times as great as the IUS stage 1 (which in turn is about 50 percent heavier than the Minuteman Stage-2 and M-X Stage-3 motors, or about three-quarters as heavy as the long, skinny Algol III first stage of Scout). The perigee stage to use half

*"... a version of the integral propulsion multimission bus (MMB) is under design/development that will place nearly 11,000 lb into stationary orbit." HAC, 1983.

the Shuttle payload capacity is about the size of MM 2 or a slightly off-loaded M-X 3. The perigee stage for one-third of capacity is about 15 percent heavier than the skinny Castor II, while the stage size for one-quarter of capacity noted on Fig. II-6, with no volume limitation imposed, is slightly smaller than the PAM-A. In all cases the market for use of the indicated solid stage would depend upon the creation of an integral-propulsion GEO-mission spacecraft of the right weight and packaging density.

For the candidate solid perigee stages listed in Table II-2, the total weight of stage plus transfer-orbit payload plus ASE is calculated using the stage characteristics listed in the table for the perigee ΔV of 8045 ft/sec and using the ASE weight derived from Fig. II-6. The resulting ratio of that total weight to 65,000 lb, i.e., the fraction of the Shuttle lift capability used, is given for each of the perigee stage candidates in the last column of Table II-2. The values indicate, for example, that the TOS is too heavy for launch in half the Shuttle payload capacity and that the PAM-DII is sized almost exactly for one-quarter of capacity.

3. Comparative Delivery Costs

From the indicated GEO payload values, assuming reasonable values for stage costs extrapolated from available estimates for PAM-D, PAM-A, and TOS, and assuming no cost for the integral propulsion, estimates can be derived for the delivery cost per pound of payload into the final GEO destination. The assumed Shuttle launch cost is from the FY 1986-88 pricing policy in FY 1986 dollars, rounded to $90M. The resulting specific delivery costs for the submultiples of the Shuttle payload capacity are given in Table II-4, compared with an internally consistent estimate for Centaur G', the only "standard stage" that uses all the payload capacity.

The selection of a stage size to use an integral fraction of the Shuttle weight-lifting capacity provides an advantage more in Shuttle use efficiency than in cost reduction. The Shuttle pricing-policy conditions which specify that the user is to pay only for the fraction of the capacity used, putting the burden on NASA to fill the rest, mean that a non-integral weight fraction leads to a non-integral price fraction also. However, the NASA policy

TABLE II-4. ESTIMATED SPECIFIC DELIVERY COSTS OF CONCEPTUAL SYSTEMS OCCUPYING SUBMULTIPLES OF THE SHUTTLE PAYLOAD CAPACITY, COMPARED WITH CENTAUR G'

N	Total Length Available (ft)	GEO PL (lb)	Stage Cost ($M)	Shuttle Cost ($M)	Total Launch Cost ($M)	Specific Cost ($k/lb)
1	60	10,350	20	90	110	10.6
2	30	4,760	15	45/.75	75	15.8*
3	20	3,030	10	30/.75	50	16.5
4	15	2,220	7	22.5/.75	37	16.6
Centaur G'	60	14,000	50	90	140	10.0

*12.6 if both satellites are from one user contracting for a dedicated launch.

for payloads that require less than the full payload capability is to recover the "full" (dedicated) launch price for utilization of 75 percent of capacity (either weight or volume, whichever use fraction is greater), so a user occupying one-quarter of capacity would pay one-third of the full price. Only if N users each intending to occupy one Nth of capacity can band together to contract for a dedicated launch, or if one user can occupy all of the capacity, could a cost saving be realized, with a potential reduction in the Shuttle portion of the cost per pound of delivered payload by one quarter of the cost for partial-payload pricing. The specific cost values for N = 2, 3, and 4 packages per launch in Table II-4 could therefore be revised downward by about one-fifth. While the cost per pound of GEO payload for full utilization of the cargo weight by a single integral-propulsion assembly does appear to be quite competitive with the cost for Centaur G', the cost of the integral-propulsion components in the GEO spacecraft are ignored and would increase the small apparent excess over Centaur G'. However, the specific cost advantage for Centaur G' holds only if the Centaur is fully loaded, with all cargo destined for one orbital plane (or nearby). For partial payloads for different orbital planes, integral propulsion has a significant advantage in increased flexibility and reduced cost per launch.

Another important consideration is that few users are indicating a desire to design their satellites to fit the capacity of the STS, but want instead to tailor the propulsion system to fit their pre-existing or mission-specific spacecraft design. Tailoring may take the form principally of off-loading the propellant of a larger stage. (Offloading of an IUS SRM-1 to about 70 percent is being considered to accommodate launch of two INTELSAT VI satellites on one Shuttle flight.) Using the TOS as an example for off-loading, Fig. II-7 shows the reduction in cost per flight relative to full cost as propellant loading is reduced from full loading with constant inert stage weight and less of the Shuttle capacity is used (assuming a $20M TOS cost independent of offloading, a $90M Shuttle cost recovered fully at 75 percent load factor, no cost of integral propulsion, and "rubber" ASE weight per Fig. II-6). The figure also shows the reduction in GEO payload with offloading; the more rapid reduction in payload than in cost per flight leads to an increase in cost per pound in GEO (the upper curve) from the $15.1 k/lb for full loading. (At the point where the weight of stage plus transfer payload plus ASE equals half the Shuttle cargo capacity, the specific cost to a single user contracting for a dedicated flight to launch two satellites would drop to $14.9 k/lb, i.e., 0.988 on the relative cost curve.)

4. Engine Sizing for Integral Propulsion

The integral propulsion in the spacecraft is to provide the insertion burn at the apogee of the transfer orbit to place the spacecraft in GEO. In addition, for a military satellite it should be able to supply efficiently a velocity increment that might be required for evasive maneuvering. Retrieval of a spacecraft from a high-altitude storage orbit is another task that may be expected of integral propulsion, but places less stringent restrictions on burn time than the other two.

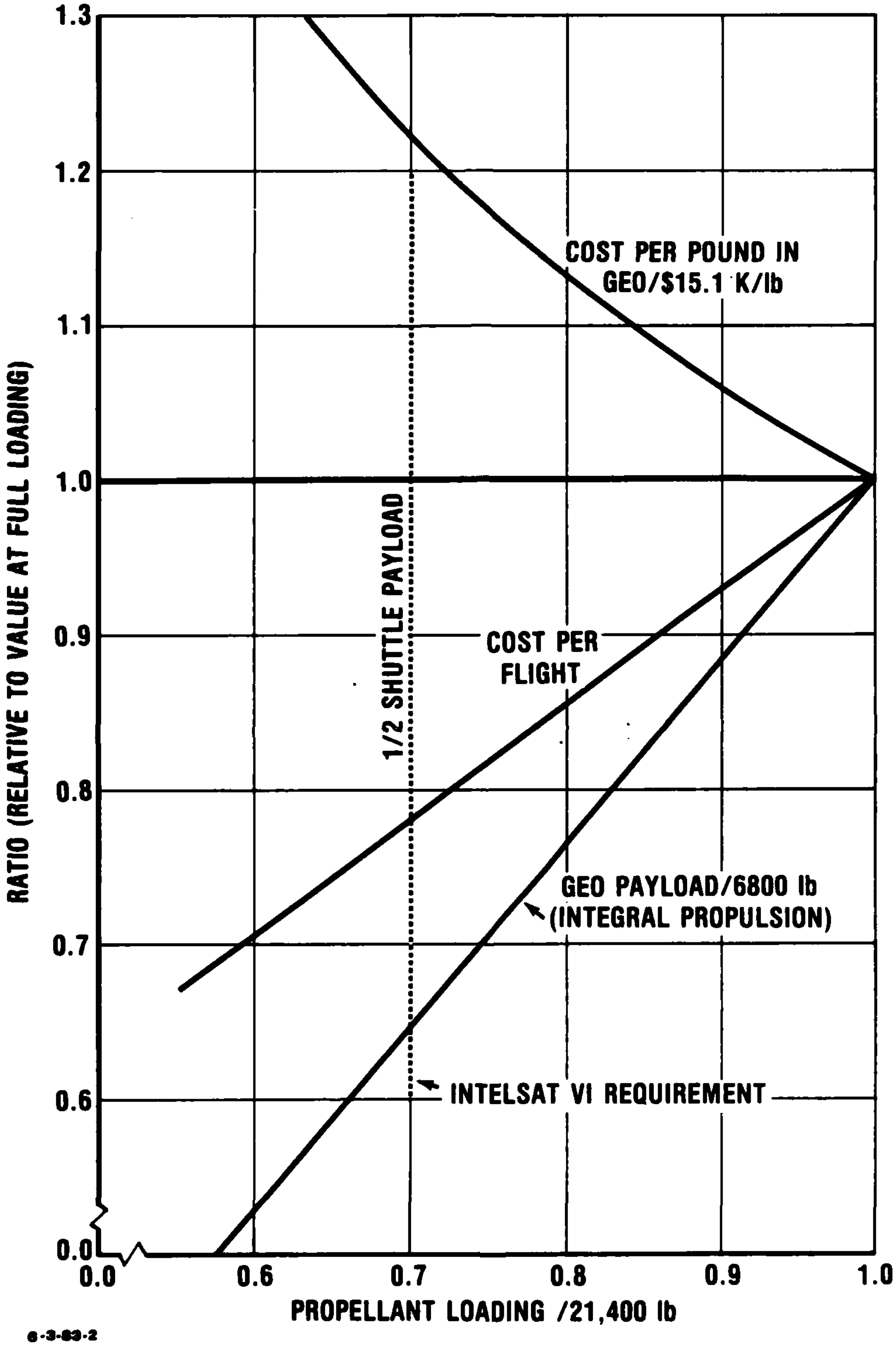


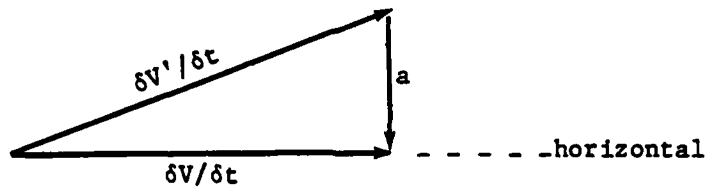
FIGURE II-7. Effect of propellant offloading on payload and cost of TOS (assumes $90M Shuttle dedicated launch cost and $20M per TOS)

For a very high ratio (e.g., 1:1) of thrust to gross spacecraft weight, both the insertion burn and the maneuver burn would approximate ideal impulsive velocity changes, reducing to negligible quantities both the integral of corrections for gravity deflection of the velocity vector (gravity losses) during the insertion burn and the finite-acceleration-time correction to the evasive-maneuver distance during the available evasion time. But a high thrust-to-spacecraft-weight ratio may lead to an inordinately high engine weight and a low thrust-to-spacecraft-weight ratio may lead to an unacceptable propellant-weight increment to compensate for gravity losses in the insertion burn.

It is of interest here to measure the balance between high engine weight at high thrust levels and high additive propellant weight for gravity losses at low thrust levels for the insertion burn and to quantify the effect of non-impulsive accelerations on maneuver displacement.

Two widely different liquid-bipropellant rocket engines, the 15,000-lb-thrust O_2/H_2 RL-10 and the 870-lb-thrust N_2O_4/MMH Orbiter RCS engine, have nearly the same thrust-to-engine-weight ratios, about 38:1. So to characterize the engine weight in the range of interest in calculations below we assume that an integral-propulsion liquid rocket engine weighs one lb for each 38 lb of thrust.

The gravity losses can be taken to be equal to the steering losses required to keep the spacecraft from falling during the insertion burn, which is timed conservatively to start at the instant that the spacecraft reaches apogee. (If the burn were started a little before apogee while the spacecraft is still ascending, no steering would be required to keep from losing altitude until apogee is reached; minimization of gravity losses by this feasible method was left to further analysis.) At each instant, therefore, the thrust vector is angled slightly above the horizontal according to the vector diagram below to produce a rate of change of velocity $\delta V'/\delta t$ which is slightly greater than the required value $\delta V/\delta t$, with the vector difference equal to the net centripetal acceleration $\underline{a}$ --



or

$$\frac{\delta V'}{\delta t} = \sqrt{\left(\frac{\delta V}{\delta t}\right)^2 + a^2}$$

and the gravity-loss velocity increment required for the burn time T is given by

$$\text{g-loss} = \int_0^T \sqrt{\left(\frac{\delta V}{\delta t}\right)^2 + a^2}\; dt - \int_0^T \frac{\delta V}{\delta t}\, dt$$

where the centripetal acceleration is given in terms of the circular orbital velocity V_c, the instantaneous velocity V and the radius of the synchronous orbit R_s by

$$a = \frac{V_c^{\,2} - V^2}{R_s}$$

An evasive maneuver that has an appreciable fraction of the maneuver time t_m taken by the acceleration time t_a will reach a displacement s in t_m smaller than the displacement s_o for instantaneous velocity change. The displacement ratio is

$$s/s_o = 1 - 1/2\; t_a/t_m$$

The fractional penalty of non-impulsive acceleration is, therefore, $1/2\; t_a/t_m$. The impulsive velocity increment must be increased by this fraction to achieve s_o with a non-impulsive acceleration.

The results of calculations using the above relations are given in Table II-5. For various insertion-burn times of an integral propulsion system with I_{sp} = 300 sec (typical of the Marquardt R-40B derivative of the RCS engine), mass fraction = 0.92 (tanks and plumbing alone--structural support assumed to be supplied by the spacecraft), and net payload in GEO = 5000 lb, the resulting values of thrust, engine weight, g-loss ΔV, g-loss-propellant weight, and the sum of the engine and g-loss-propellant weights are given. In addition, for a hypothetical 75-nmi displacement in 30 minutes, the required burn time and non-impulsive displacement penalty are tabulated for each thrust level defined for the insertion burns.

TABLE II-5. INTEGRAL PROPULSION CHARACTERISTICS:
Thrust, g-loss, Propulsion Weight, Maneuver Burn Time and Non-Impulsive Penalty
(I_{sp} = 300 sec; T/W_e = 38; mass fraction = 0.92, Net GEO Payload = 5000 lb)

GEO Insertion Burn						75 nmi/30 min Maneuver	
Burn Time (min)	Thrust (lb)	Engine Weight (lb)	g-loss ΔV (ft/sec)	g-loss Prop (lb)	"Total" Propulsion (lb)	Burn Time (sec)	Non-Impulsive Penalty (percent)
1	22,470	591	0.1	0.1	591	2	0.05
2	11,230	295	0.4	0.4	296	4	0.11
5	4,500	118	1.6	1.7	120	10	0.27
10	2,250	59.3	5.9	6.1	65.4	19	0.53
15	1,500	39.6	12.6	13.0	52.6	29	0.80
20	1,130	29.7	22.1	22.9	52.6	38	1.06
30	760	19.9	49.1	50.5	70.5	57	1.58
40	570	15.1	85.5	88.2	103.3	75	2.09
50	460	12.2	130.6	135.1	147.3	93	2.59
60	390	10.3	182.4	189.4	199.7	110	3.07

For the range of insertion-burn times from one minute to one hour the thrust level drops from 20,000 lb to 400 lb, the engine weight drops from 600 lb to 10 lb, the g-loss-propellant grows from 0.1 lb to 200 lb, and the sum of the engine weight and g-loss-propellant weight drops from 600 lb to the minimum in the table of about 52 lb between the 15-min-burn entry and the 20-min-burn entry and rises back to 200 lb. For use of these propulsion systems for the evasive maneuver, the burn times grow from 2 sec to 110 sec and the penalty for non-impulsive acceleration remains small: 0.05 percent to 3 percent over the range of thrust levels.

To show graphically the behavior of engine weight and g-loss-propellant weight to determine the optimum thrust level, these weights and their sum are plotted against GEO-insertion-burn time in Fig. II-8. The monotonic decline in engine weight and monotonic increase in g-loss-propellant weight with increasing burn time combine to form a well-defined minimum at about 17 minutes burn time (about 1,300-lb thrust). At the 700-lb-thrust level of the Marquardt R-40 engine (and a 32-minute burn time), the weight sum has increased by only about 25 lb from the minimum, and from Table II-5, the non-impulsive penalty is about 1.7 percent of the approximately 250 ft/sec maneuver, or about 4 extra ft/sec. The method suggested above to minimize the g-losses would move the minimum to higher burn times; a weight sum of only 50-80 lb for items sensitive to burn time has already become a tiny component of the 5000-lb satellite plus about 250 lb of total integral-propulsion-system dry weight.

5. Recapitulation

Assessment of the promise of the current conventional form of integral propulsion requires determining the size, payload, and launch costs of candidate solid perigee stages and evaluating the tradeoffs in selecting the thrust level of the liquid propulsion systèm built into the mission spacecraft.

The particular GEO perigee stage, that, with transfer-orbit payload and ASE, would use all the 65,000-lb Shuttle payload capability, would be about one-and-a-half times as heavy as the IUS SRM-1; scaled from that stage (actually from the TOS) it would deliver about 20,500 lb into the transfer orbit and, with an integral propulsion system having characteristics similar to the Marquardt R-40 engine, would deliver a net payload of about

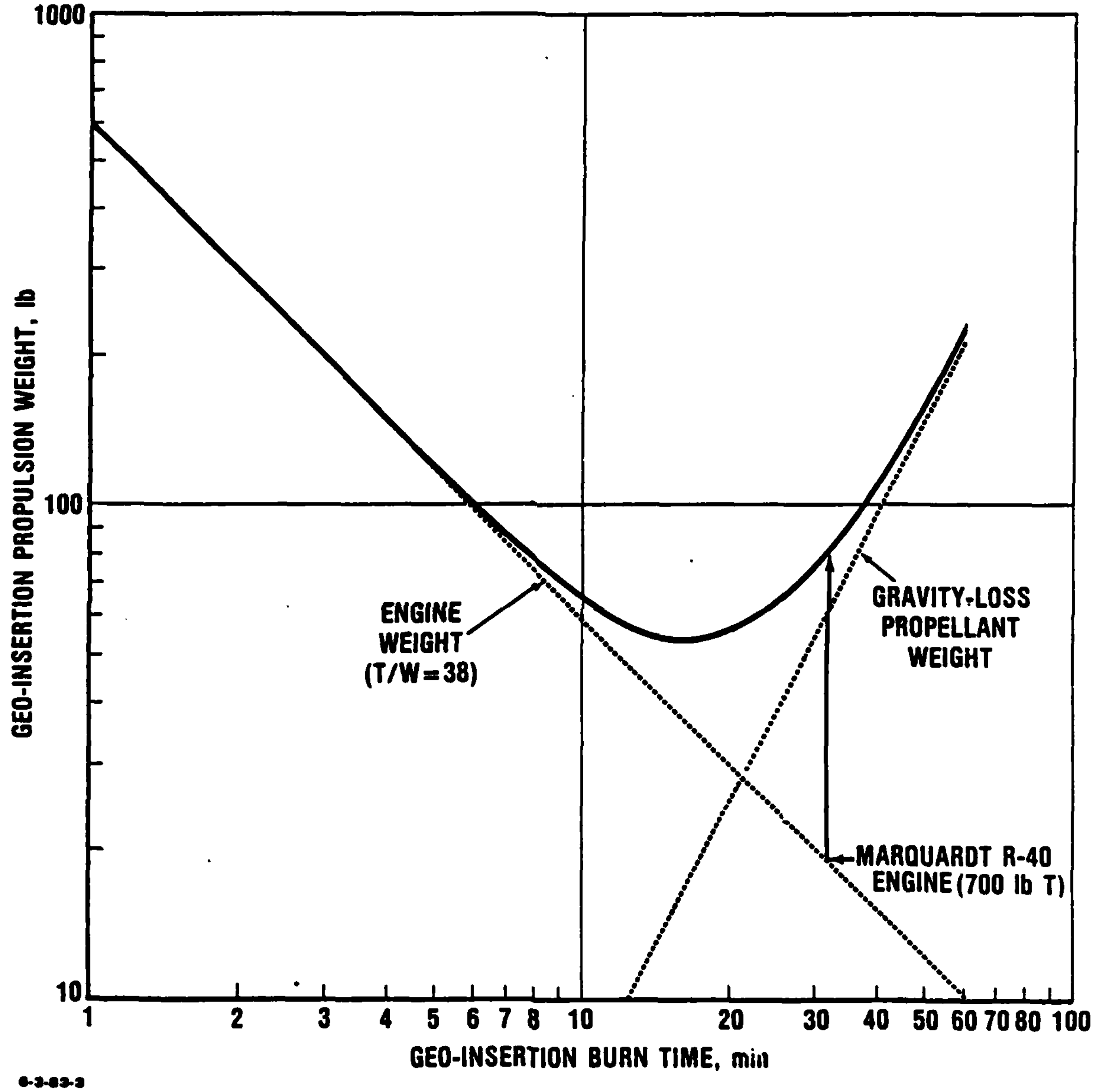


FIGURE II-8. Integral-propulsion sizing considerations for GEO insertion (net payload in GEO: 5000 lb, apogee propulsion: I_{sp} = 300 sec, λ' = 0.92)

10,350 lb into GEO. The TOS is too heavy for two-at-a-time launch on the Shuttle but with offloading of 30 percent of its propellant would fit half the Shuttle's payload capacity and each of such a pair would deliver about 8,700 lb to transfer orbit and, with integral propulsion similar to that above, about 4,400 lb net to GEO (a spinning version of the IUS SRM-1 as to be used with INTELSAT VI would have a lower inert stage weight than TOS and slightly more payload). The PAM-DII is sized almost exactly for four-at-a-time launch giving about 4,000 lb each in transfer orbit, and, with integral propulsion, a net GEO payload of about 2,000 lb for each of the four.

Estimates here of the specific delivery cost of GEO payload indicate that, while there is no per-pound cost advantage for integral propulsion over Centaur G', say, the cost per launch for payloads smaller than the capacity of the Centaur G' can be minimized by tailoring the perigee stage and the integral propulsion to the spacecraft weight.

In the tradeoff in selecting the thrust level for the integral liquid propulsion system that provides the GEO-insertion ΔV, high engine weight at short burn times is to be balanced against high g-loss-propellant weight at long burn times. A minimum sum of engine weight and g-loss-propellant weight of about 54 lb for a 5000-lb example satellite is obtained for a burn time of about 17 minutes (about 1,300-lb thrust), with the sum of the weights remaining at or below 80 lb for thrust levels between about 700 lb and 2,800 lb. In this thrust range, the non-impulsive ΔV requirement for an example maneuver of 75 nmi in 30 minutes exceeds the ideal impulsive ΔV requirement by only about one percent. The 700-lb-thrust Marquardt R-40 engine therefore appears to be a good candidate for satellites in the 5000-lb class.

C. ADVANCED INTEGRAL-PROPULSION CONCEPTS

1. Introduction and Background

Presented in the previous section were the results of an introductory assessment of a "hybrid" integral propulsion system (IPS), in which a simple spinning solid-propellant-rocket stage was to provide all of the perigee kick ΔV for injection into a geosynchronous transfer orbit, and a liquid-rocket propulsion system built into the geostationary spacecraft would supply the apogee ΔV into GEO. That system is one used historically by Hughes satellites. TRW proposes another form of IPS in which both apogee kick and perigee kick are to be supplied by the same liquid propulsion system, either "integrated" (bolted on) or "integral" (built in) to the GEO spacecraft. A variant of this single-stage or "unitary" IPS would involve dropping tanks in midcourse to improve the mass ratio (initial to final mass).

The Transfer Orbital Stage (TOS) proposed by Orbital Systems Corporation (OSC) is to be a three-axis-stabilized (not spinning) stage based on the first-stage motor (SRM-1) of the Inertial Upper Stage (IUS). The SRM-1 is built by the Chemical Systems Division (CSD) of United Technologies Corporation. The SRM-1 is also to be used in a spinning version by the Hughes INTELSAT VI, with the solid propellant offloaded to about 70 percent so that two INTELSAT VIs can be delivered by one Shuttle flight. While OSC has priced the TOS at about $20 million, CSD is selling the SRM-1 (off-loaded) to Hughes for under $2 million (1982) each for a buy of six, plus the non-recurring cost of two spinning qualification firings. The choice of three-axis stabilization or spinning would depend on the design of the satellite to be delivered, but the more conservative TOS (more expensive, heavier) is adopted here to typify the perigee kick stage nearest to the size that would utilize the full Shuttle cargo bay; larger stages are being considered for development (e.g., the Thiokol IPSM-III and growth versions of the TOS), and it is of interest to determine their potential payload advantage over TOS.

Cost estimates from Hughes for a hybrid IPS and from TRW for a unitary IPS indicate that either, including non-recurring costs, would be cheaper than Centaur for a satellite buy of two, and that the relative cost of the two forms of IPS would probably depend on the detailed design of the satellite. In fact, the costs of the two forms of IPS may be close enough together (well below the Centaur) that the choice between the two may be made on the basis of performance rather than cost.

With this background, the principal questions addressed herein are the following:

1. What is the optimum size of the perigee kick stage in a "hybrid" IPS?
2. What is the relative performance of "hybrid" and "unitary" IPS? and
3. How does the payload performance into GEO relate to the payload into 65-deg-inclination or 8-deg-inclination 24-hr circular orbits? What is the optimum Shuttle-parking-orbit inclination for the 65-deg destination?

2. Hybrid IPS Optimization

The perigee-stage propellant weight to utilize all of the Shuttle's lift capability into a 160-nmi 28.5-deg parking orbit (less ASE weight; with the perigee stage sized to provide all the GEO transfer ΔV) is about 32,000 lb, per Section IIB. To utilize half the Shuttle's lift capability--to enable launch of two spacecraft in one Shuttle flight--the perigee-stage propellant weight should be about 15,000 lb. The propellant weight of the TOS, Table II-6, is about 21,000 lb, too small to utilize all the Shuttle's lift capability (and deliver all the GEO transfer ΔV to the rest of the separation weight), but large enough so that it could be off-loaded to about 70 percent of full propellant capacity to deliver two spacecraft per Shuttle flight, albeit with some excess inert weight over an ad hoc design. It is in the off-loaded mode that the INTELSAT VI (by Hughes) will use the IUS SRM-1 (in a spinning version, not the 3-axis-stabilized TOS--with some weight reduction from TOS) to allow two of the satellites to be launched at the same time by the Shuttle to minimize transportation costs.

While it would be undesirable for a solid-propellant stage to provide more than the GEO-transfer ΔV, because such a condition would require restart at apogee and solid motors are difficult to stop and restart, there is no reason why the solid-propellant stage should not provide less than the GEO-transfer ΔV: if the solid stage cannot deliver the GEO-transfer ΔV, the IPS can supply the remainder of the GEO-transfer ΔV, as well as the

TABLE II-6. TOS PERFORMANCE PARAMETERS
(FROM OSC, 1983)

	Baseline	Advanced	Growth
Max Propellant Weight, lb	21,404	25,086	30,756
Stage Burnout Weight, lb	2,586	2,586	2,970
Propellant I_{sp}, sec	295	295	295
Motor Length, in.	105	105	119
Motor Diameter, in.	91	91	91
Burn Time, sec	150	159	208
Max Transfer Capability, lb	13,000	16,000	19,000+

apogee ΔV. The low-thrust IPS may have to wait to fire until the next perigee to minimize gravity losses, but such a requirement would add only a few hours to the transfer time to GEO. By this means the IPS can be allowed to grow to utilize more (or all) of the Shuttle's net lift capability while using an existing solid stage (e.g., TOS) smaller than the 32,000-odd pounds otherwise required to place the remainder of the Shuttle's net lift capability into a GEO-transfer orbit.

The TOS, with just the payload weight it can deliver to a GEO-transfer ΔV (and with the ASE weight per Fig. II-6), fills only about 69 percent of the 65,000-lb Shuttle lift capability into a 28.5-deg, 160-nmi parking orbit. The GEO payload consistent with this loading is advertised by OSC to be 6800 lb with a "maximum performance AKS." (AKS = apogee kick stage, e.g., IPS). We can deduce the required IPS mass fraction for a typical IPS engine performance, and scale the IPS up from the size for the 6800-lb payload to determine the performance of the resulting overloaded-TOS/IPS combination. If we assume the IPS uses the Shuttle RCS engine, modified with a larger nozzle expansion ratio to give an I_{sp} of 300 sec (Marquardt R-40 engine), the IPS mass fraction required to give just the advertised TOS GEO payload is 0.9176.

The increase in GEO payload as the IPS is increased in size, overloading the TOS so it provides less and less perigee ΔV, is shown in Fig. II-9. If the Shuttle's maximum separation weight is 57,000 lb (65,000 lb minus 8,000 lb of ASE), the GEO payload is 10,600 lb for overloading of TOS with

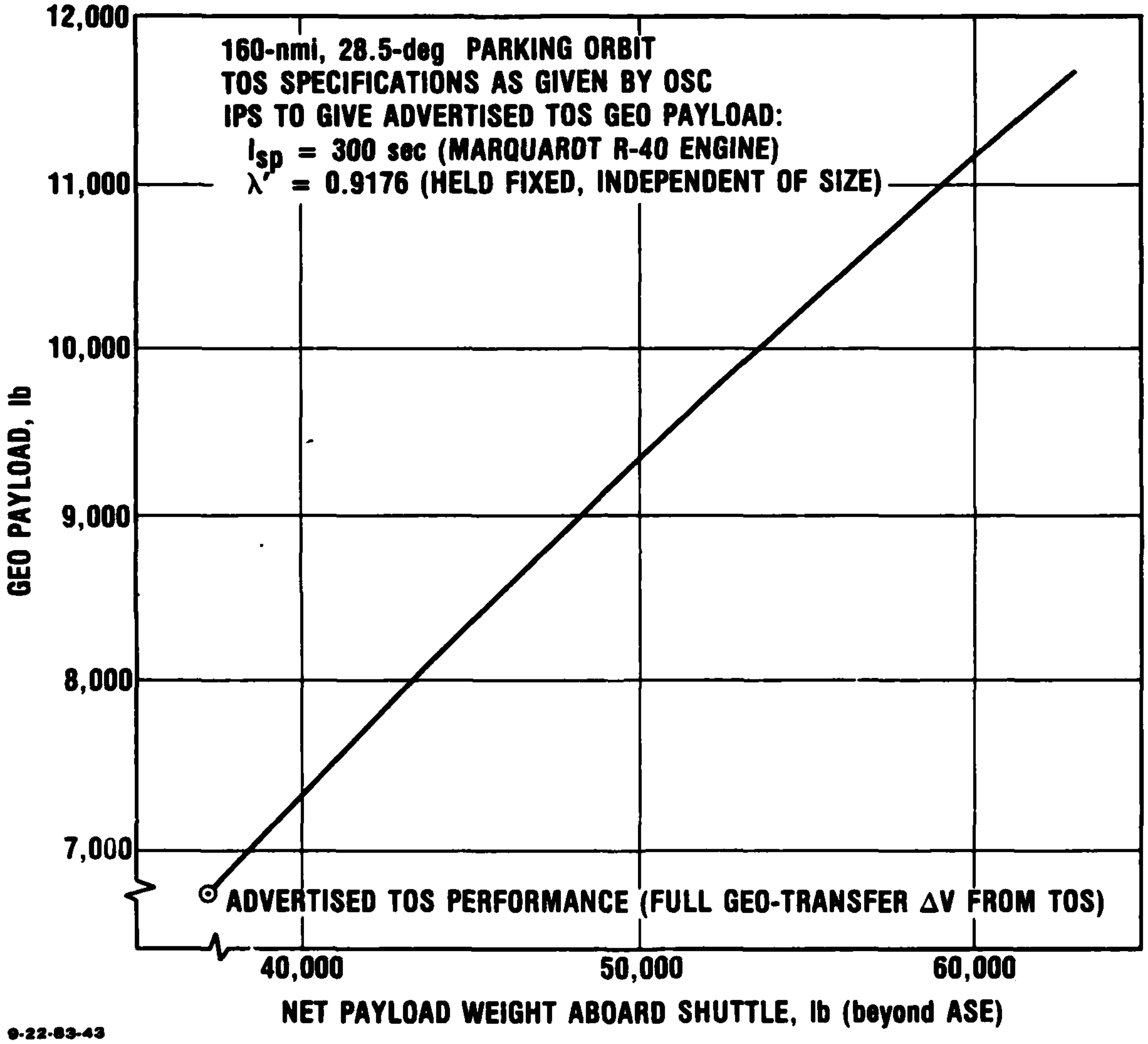


FIGURE II-9. GEO payload with overloading of TOS; integral propulsion provides part of perigee kick

IPS to reach that maximum separation weight. The curve in Fig. II-9 assumes that the IPS mass fraction remains at 0.9176 as the propellant weight is increased, ignoring the potential increase in mass fraction that would come from decreased tank surface-to-volume ratio as volume is increased, which would increase the payload further.

In the case where the TOS is overloaded to a total weight (TOS plus IPS plus payload) of 57,000 lb, the TOS injects the payload/IPS into a 160 x 4500 nmi elliptical orbit. The IPS would fire about three hours later at the next perigee, providing about 3500 ft/sec to raise the apogee to 19,323 nmi, and would fire again in another 5-1/4 hours to circularize the 10,600-lb payload at apogee.

Noting the degree of overloading (up to about 20,000 lb) indicated in Fig. II-9, it is of interest to determine the potential reward of increasing the size of the solid perigee stage to reduce the overloading. The solid stage is scaled from TOS by keeping the same mass fraction, 0.8922, as the propellant weight is varied. The size of the IPS is adjusted to fill the remainder of the 57,000-lb separation weight assuming a constant mass fraction, 0.9176 (the same as that assumed in Fig. II-9). The GEO payload of the combination is calculated, for the assumed I_{sp}'s of 295 sec (TOS) and 300 sec (IPS), as a function of scaled-TOS propellant weight over the range from zero (all IPS) to 32,600 lb (solid stage provides all the GEO-transfer ΔV) and the results are plotted in Fig. II-10. The optimum propellant weight for the scaled TOS is 24,300 lb, 2900 lb greater than TOS; the maximum GEO payload is only 22 lb greater than that with the overloaded TOS, however. The velocity split is about 5300 ft/sec for the optimum scaled TOS and 8600 ft/sec for the IPS. Note that the GEO payload with the solid-stage size (32,600 lb) that delivers all the GEO-transfer ΔV (cf. Section IIB) is about 250 lb less than that with the overloaded TOS. Also note that, even for solid-stage sizes as small as the PAMs (4400-7600 lb of propellant), a GEO payload delivery capability of about 10,000 lb appears possible with overloading of the PAMs to the 57,000-lb limit. Perigee g-losses during the IPS burn(s) to supply the rest of the GEO-transfer ΔV, not evaluated here, would drive the selection of stage size toward the larger sizes.

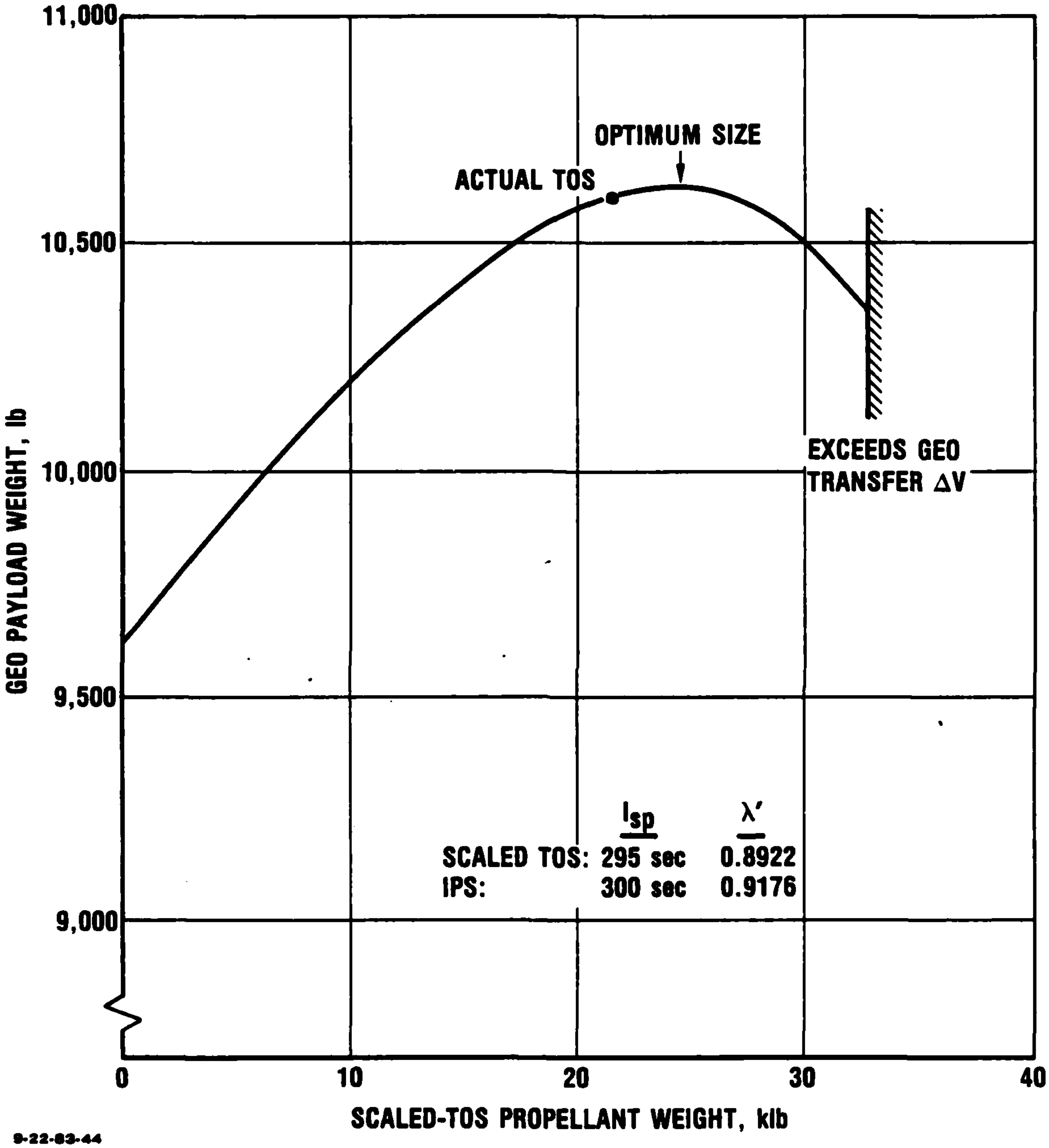


FIGURE II-10. Solid-stage-size influence on GEO payload (solid stage overloaded to 57,000-lb total separation weight)

3. Comparative Performance of Unitary IPS

The payload for zero scaled-TOS propellant weight in Fig. II-10 represents the performance of a single-stage or "unitary" IPS; this payload value is about 1000 lb less than that with the overloaded TOS. (Performance of a stage-and-a-half drop-tank configuration, while undoubtedly better than that of single-stage, was not calculated here.) TRW indicates gravity losses for the unitary IPS' low thrust (700 lb) of about 200 ft/sec for multi-perigee burns (gravity losses are ignored in the performance calculations in this analysis).

Sensitivities of the payload values to changes (possible uncertainties) in IPS mass fraction, I_{sp}, ASE weight, and mission ΔV were computed for the two IPS modes; the results are as follows:

		Sensitivities (Partial Derivatives)			
IPS Mode	GEO Payload (lb)	$\Delta PL/\Delta\lambda'$ (lb/point)	$\Delta PL/\Delta I_{sp}$ (lb/sec)	$\Delta PL/\Delta ASE$ (lb/1000 lb)	$\Delta PL/\Delta(\Delta V)$ (lb/100 ft/sec)
Hybrid	10,600	242	43	180	140
Unitary	9,620	514	70	163	150

The sensitivities to the mass fraction and I_{sp} of the IPS ($\Delta PL/\Delta\lambda'$ and $\Delta PL/\Delta I_{sp}$) are about twice as great for the unitary IPS as for the overloaded-TOS hybrid IPS. The sensitivities for ASE weight (or Shuttle delivery capability) and mission ΔV were about equal for the two modes, with surprisingly small values. The ASE weight derived by TRW is about 3000 lb less than assumed here (giving a separation weight of 60,000 lb instead of 57,000 lb, also equivalent to an increase in Shuttle capability to 68,000 lb while keeping the 8000-lb ASE weight) and the resulting improvement in GEO payload is about 500 lb for either mode. The gravity losses calculated by TRW for the unitary IPS, about 200 ft/sec, lead to a payload penalty of only about 300 lb. Sensitivities of the overloaded-TOS hybrid system to solid-stage parameters are 85 lb/point and 21 lb/sec of I_{sp}.

TRW considers two forms of unitary IPS: (1) "integral," i.e., built into the spacecraft structure, as well as making use of spacecraft control systems, etc., and (2) "integrated," bolted on to the spacecraft structure externally, with the control signals between the satellite and the propulsion system fed through the structural interface. If some propellant tanks must already be incorporated into the spacecraft for repositioning/maneuvering, then the fully integral IPS might be introduced merely by lengthening the tanks with cylindrical sections, while the "integrated" IPS would require complete, separate, dedicated tanks.

The thickness t of the wall of a cylindrical section of a pressurized tank is set by hoop stresses, and is given in terms of the diameter D, the internal pressure p, the material yield strength Y, and a safety factor f as

$$t = \frac{fpD}{2Y} \quad .$$

The mass fraction λ' of a cylindrical section of tank (a measure of the ultimate mass fraction to be achieved by an incremental capacity of fully integral tanks) is given in terms of the density of the tank material ρ_{wall} and the density of the propellant ρ_{prop} by

$$\lambda' = \frac{1}{1 + \frac{2fp}{Y} \frac{\rho_{wall}}{\rho_{prop}}} \quad .$$

For an aluminum wall (ρ_{wall} = 168.4 lb/ft^3, Y = 20,000 psi and f = 1.5) and N_2O_4/MMH propellant at a mixture ratio of 1.9 (ρ_{prop} = 73.2 lb/ft^3) and a pressure of 100 psi, the value of the mass fraction of an incremental tank volume comes out as 0.9666. If the 0.9176 assumed before for the mass fraction of IPS represents a value for dedicated tanks, the difference between the values, a $\Delta\lambda'$ of about 0.05, may give a measure of the difference between "integral" and "integrated" IPS, i.e., about 2500 lb of payload for a "unitary" system, or about half that for a hybrid system. Further, the weight of the structural interface, estimated by TRW to be in the 600-lb range for a 5000-lb spacecraft, must be subtracted from the payload for the "integrated" version. An example of "integrated" IPS may be seen in the Convair Spacecraft Maneuver Module, Fig. II-11, developed, built, and tested on company funds (a measure of the cost of IPS).

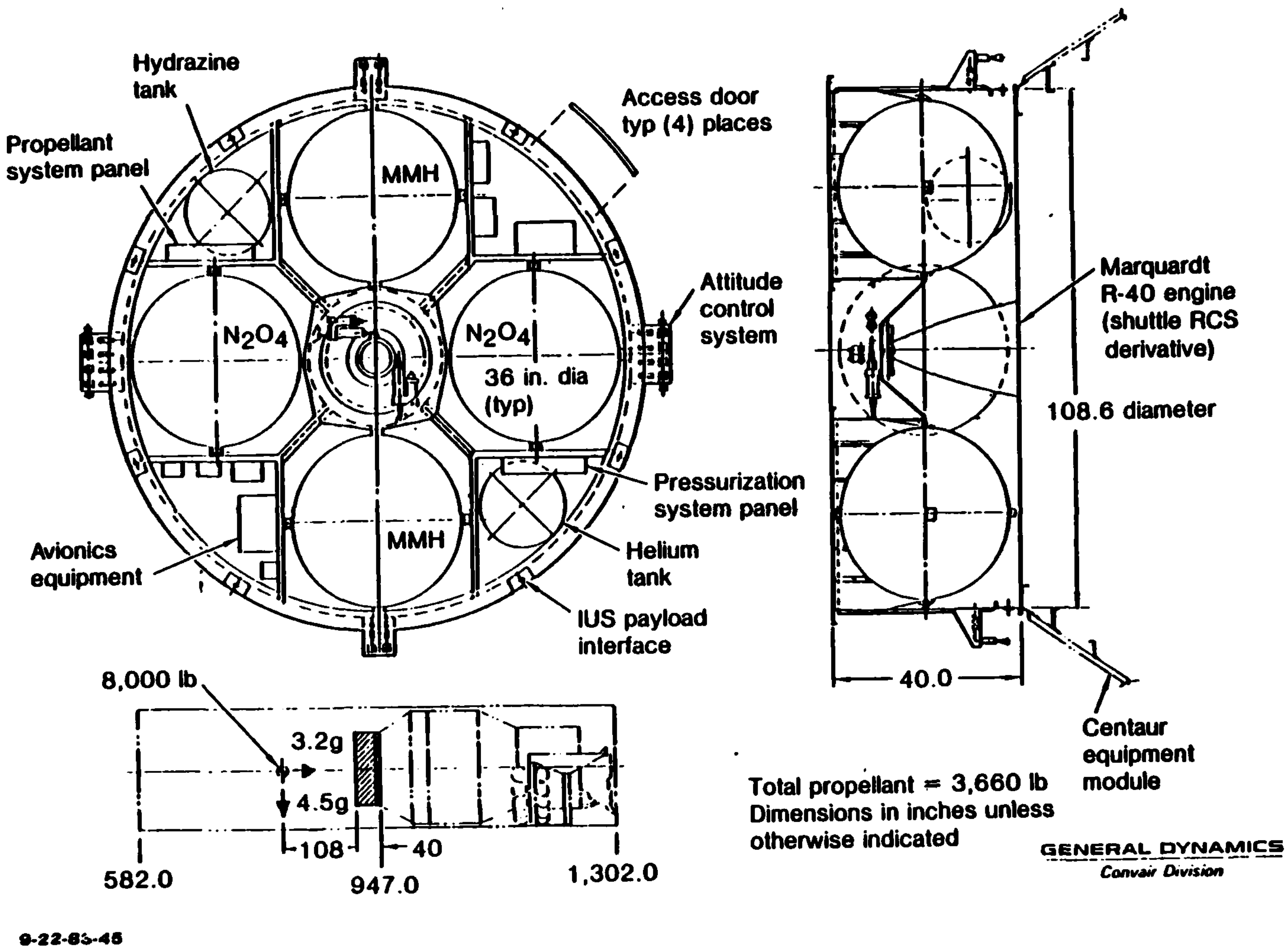


FIGURE II-11. Inboard profile of the spacecraft maneuver module (courtesy General Dynamics, Convair)

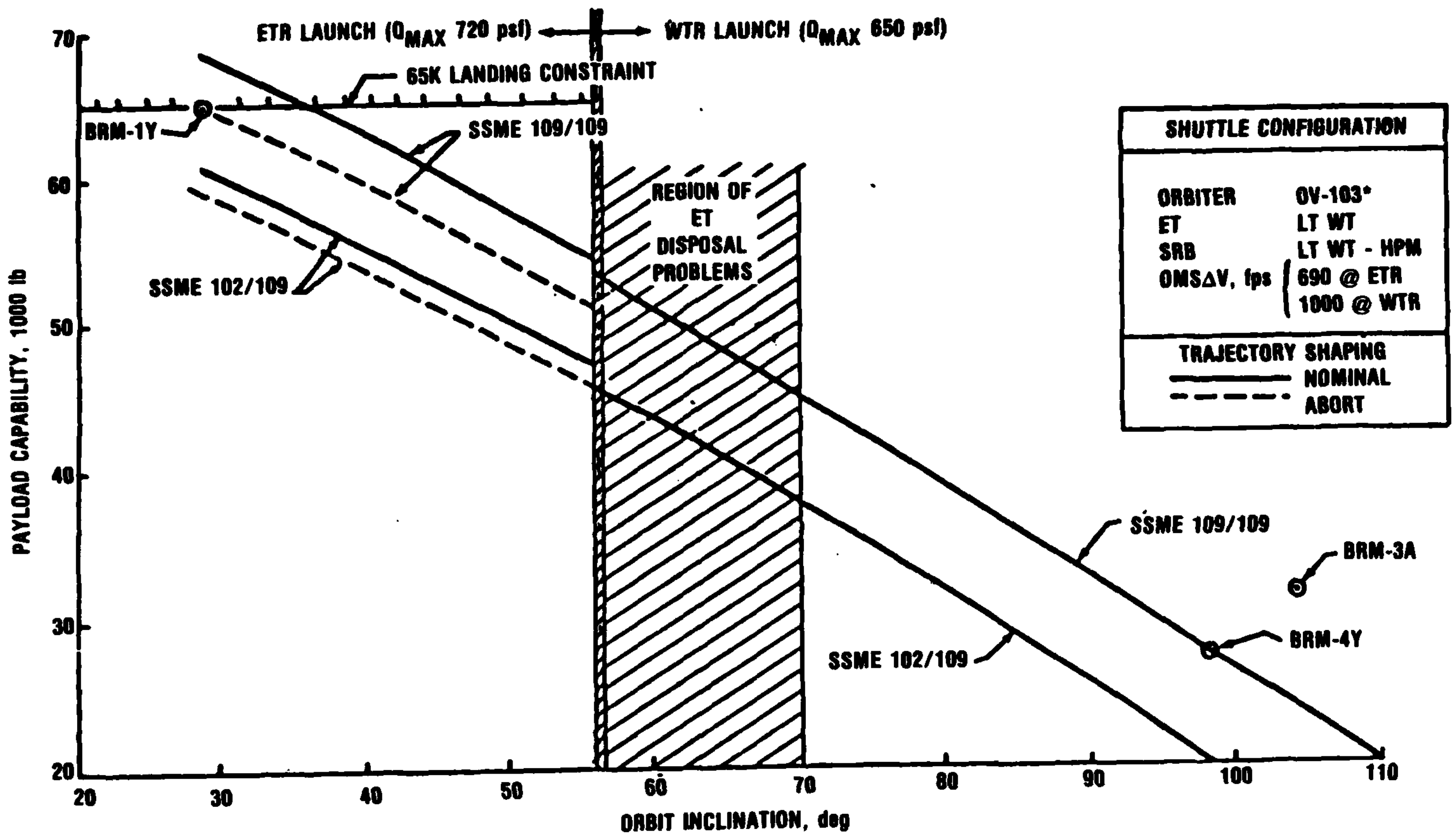
4. IPS Payload to Other Inclinations

Other inclinations of 24-hour circular (geosynchronous) orbits under consideration are 8 degrees and 65 degrees. It is of interest here to relate the GEO payloads that have been determined above with the payload capabilities of IPS into these other inclinations. Of particular interest for the 65-deg payload is the effect of the decrease in the Shuttle lift capability as inclination increases, while the plane-change requirement is diminishing and the fraction of the separation weight delivered into the destination orbit is increasing.

The dependence of Shuttle lift capability on the inclination of the parking orbit is shown in Fig. II-12. The curve for "Nominal" trajectory shaping for SSME 109/109 is taken as typical of Shuttle performance in the late 1980's. The 65,000-lb landing constraint sets a constant limit on lift capability between 28.5 deg (the minimum achievable from KSC) and about 36.5 deg of inclination. The separation-weight capability is found from the lift capability by subtracting the ASE weight determined from Fig. II-6 (diminishing from a value of 8000 lb at a 57,000-lb separation weight as separation weight is reduced).

The plane change from 36.5 deg to 65 deg is the same as from 28.5 deg to 0 deg, and, since the Shuttle payload into 36.5 deg in Fig. II-12 is the same as in 28.5 deg, the payload into a 65-deg geosynchronous orbit from a 36.5-deg parking orbit is the same as the GEO payload. The payload into an 8-deg geosynchronous orbit from 28.5 deg is about 750 lb more than the GEO payload; from 36.5 deg it is the same as the GEO payload.

The 65-deg geosynchronous payload dependence on Shuttle parking-orbit inclination is shown in Fig. II-13 for both the overloaded-TOS hybrid (solid curve) and unitary (dotted curve) versions of IPS. Each curve shows a maximum not far from a 36.5-deg parking orbit inclination (which gives the same as GEO payload). The decrease in Shuttle payload at higher inclination outweighs the increase due to diminishing plane change. At the optimum Shuttle inclination for the overloaded-TOS hybrid IPS, 39.1 deg, the 65-deg-geosynchronous payload is only 21 lb more than the reference GEO payload.



*Based on projected weight JSC-09095-71 (April 1983)

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FIGURE II-12. Space Shuttle payload deployment capability versus inclination (crew/days 2M/1D, orbit altitude 150 nmi) (from JSC, 1983)

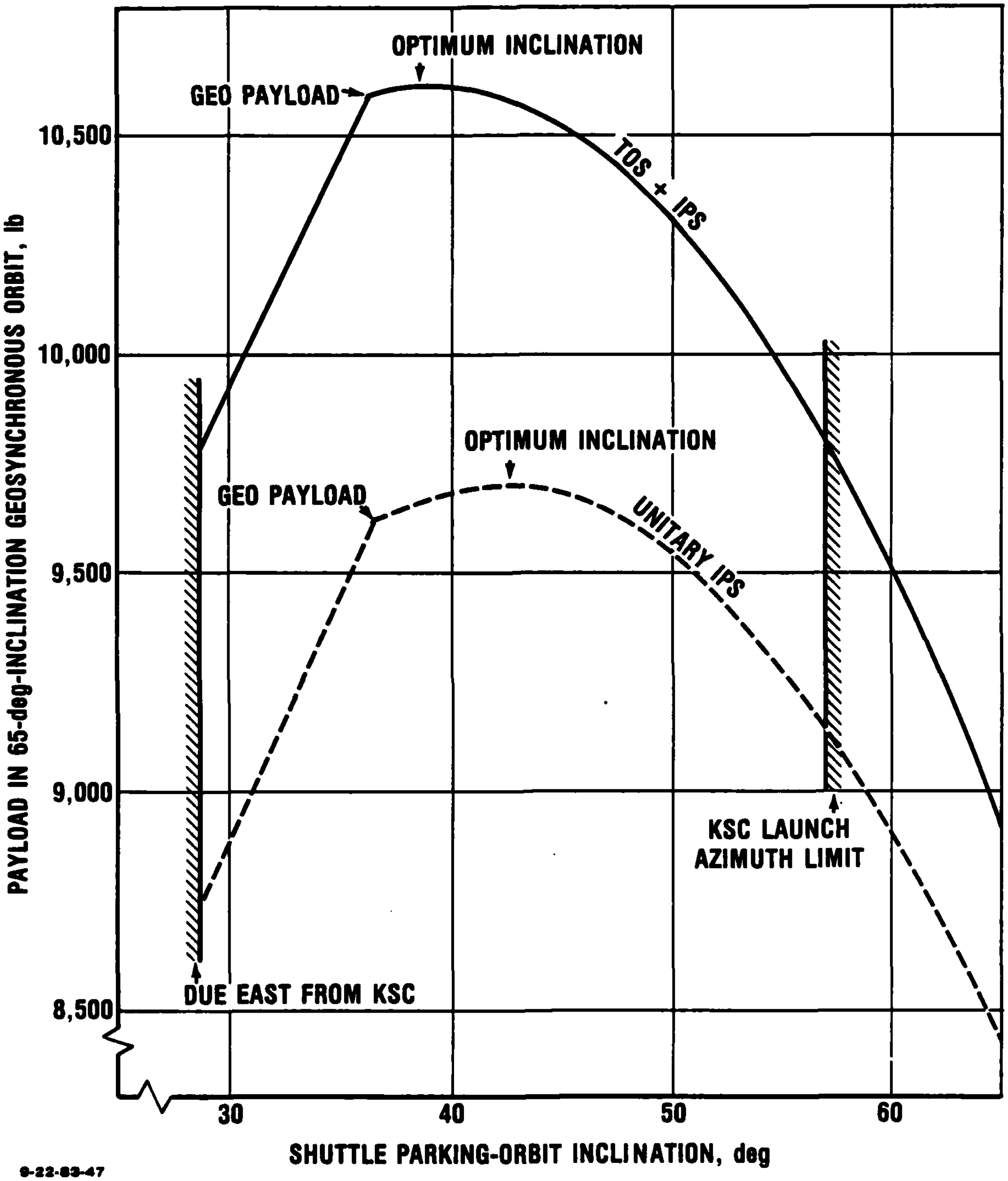


FIGURE II-13. Parking-orbit-inclination influence on payload into 65-deg-inclination geosynchronous orbit (overloaded TOS or unitary IPS using all Shuttle capability less ASE weight)

At the optimum Shuttle inclination for the unitary IPS, 42.05 deg, the 65-deg payload is 80 lb more than the GEO payload. From a Shuttle parking orbit of 36.5-deg inclination an equal-sized IPS could be used for both the 8-deg and the 65-deg destinations.

Since 36.5 deg is halfway between 8 deg and 65 deg and 28.5 deg from each, the Shuttle could launch two approximately-4800-lb spacecraft, the GEO payload capability from half the cargo bay per Section IIB, one into each orbit, using individual IPS for each one. Centaur would have to provide the full 57-deg plane change after dropping one spacecraft off to perform the same feat, involving a prohibitive ΔV cost of the order of 10,000 ft/sec.

If the longitudes of the ascending nodes of the different destination orbits were spaced 90 deg apart, a wait of about 14 days in a 36.5-deg parking orbit by the second payload/IPS/perigee stage would allow the parking orbit's plane to precess by 90 deg to come into coincidence with the second plane.

5. Recapitulation/Implications

The analysis here indicates that there exists an optimum combination of solid perigee stage and IPS between the extremes typified by the designs of Hughes (solid stage provides all the GEO-transfer ΔV) and TRW (IPS provides both the GEO-transfer and the apogee-circularization ΔVs). The TOS is very close in size to the optimum perigee-kick stage used in an overloaded mode to fill the Shuttle's maximum-separation-weight capability. The TOS overloaded with IPS and payload to add up to a 57,000-lb separation weight is calculated to deliver about 10,600 lb to a geostationary orbit. From a Shuttle parking orbit of 36.5-deg inclination, the GEO payload weight could be delivered to either an 8-deg or a 65-deg-inclination 24-hour orbit with a common-design IPS.

If the cost of IPS is indeed as low as estimated by Hughes and TRW, and evidenced by many commercial communications-satellite programs and by the Convair company-funded Spacecraft Maneuver Module, IPS should be preferable to the like-performance Centaur G for any spacecraft buy of more than one unit. The time of crossover in costs of IPS and an OTV would be even further in the future than the crossover for Centaur and OTV. Wide use of IPS rather than an OTV could delete the OTV-servicing transportation-node functions from justification for a Space Station until manned geostationary (or lunar, etc.) missions were required.

III. SPACE TRANSPORTATION COSTS AND OPERATIONS

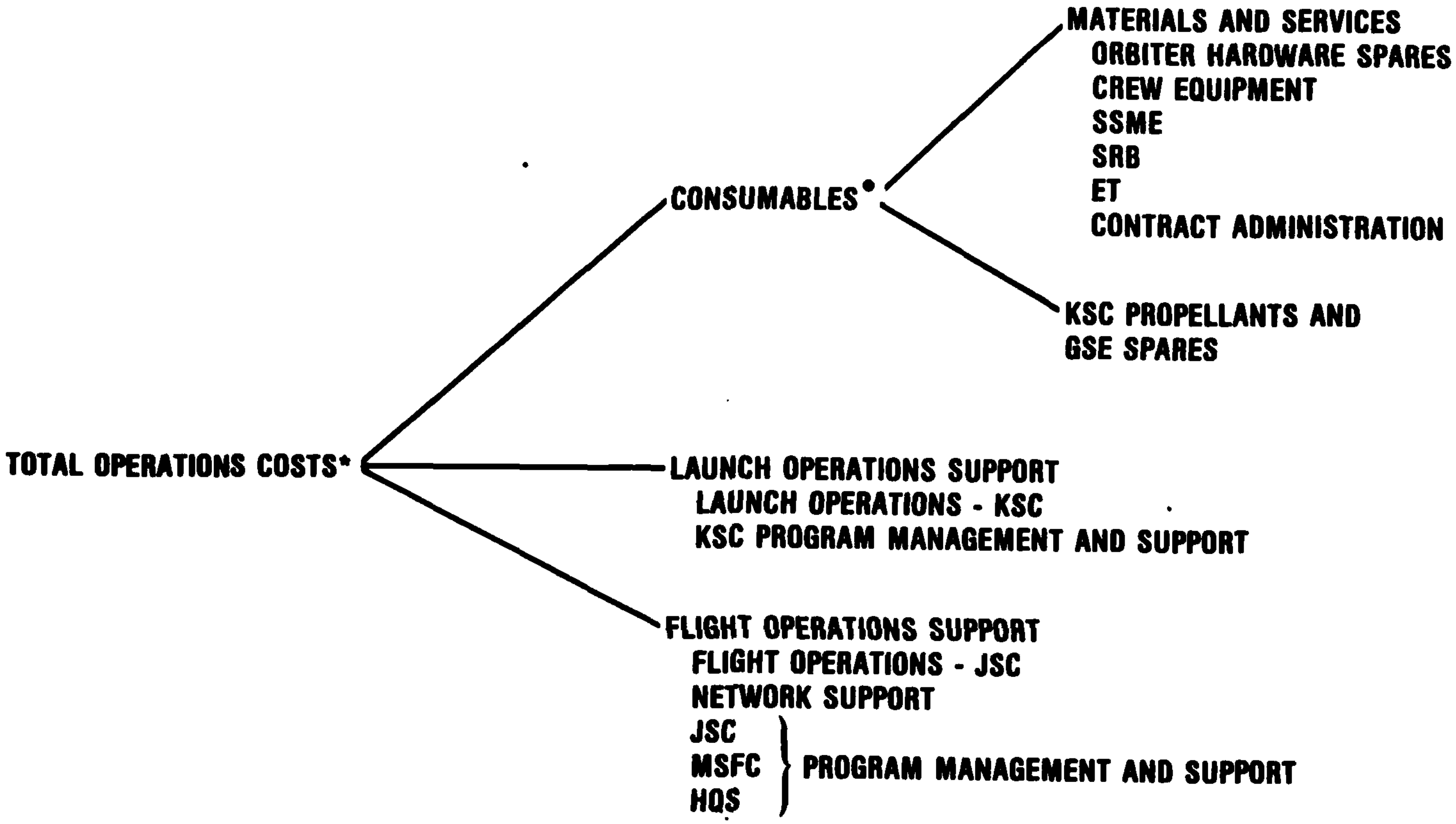
Four successful operational flights of the Space Shuttle have taken place since November 11, 1982. A variety of mission tasks have been completed, including the launching of several commercial communication satellites and one U.S. Government satellite, TDRS-A. The accumulated experience thus far acquired in Shuttle launch and flight operations and in other launch-related tasks has generated the beginning of a realistic data base for use in forecasting cost trends in these areas. Some examples are presented herein. At the same time, there is considerable interest throughout the user community in the comparative cost of a Shuttle launch and an ELV launch. This interest has been highlighted by the White House press release of May 16, 1983, in which the President announced that the U.S. Government fully endorses and will facilitate commercial operations of ELVs by the U.S. private sector. Inasmuch as the loss of a commercial Shuttle flight to an ELV will reduce the Shuttle flight rate the net effect will be an increase in the total cost of Shuttle operations to the U.S. Government. An assessment of the magnitude of this cost increase is included in this section.

A. SHUTTLE OPERATIONAL COST TRENDS

IDA, 1982 contains a discussion of Shuttle launch costs and charges for non-government users and the DoD based on NASA's pricing schedule covering the period FY 1986-1988. More recently NASA has projected its annual cost per flight estimates through FY 1994 in a major step toward establishing a firm pricing base for flights beyond FY 1988. In this section details of the NASA studies are examined and implications drawn as to possible impacts on DoD Shuttle Operations Costs in the future.

Figure III-1, based on information contained in KSC, 1983, delineates the major sources of hardware and activities that contribute to the total Shuttle Operations Costs. As indicated, the total costs are generated in three principal areas--the consumables (including associated administrative costs), launch operations (including all program management and support activities), and flight operations (including network support and staffing support provided by various NASA units). The chart applies specifically to NASA launches from KSC but a similar diagram could be constructed for operations at VAFB. NASA has examined and assessed in some detail the cost components of these activities and has synthesized an overall estimate of the annual total operation costs of the Space Shuttle over a twelve-year span, FY 1983-1994). Two traffic models were used--the current official one that culminates in a maximum flight rate of 24 per year, and an unrestrained traffic model that peaks at a flight rate of 40 per year. NASA and DoD facilities at KSC and VAFB can handle the higher flight rate but additional funds would have to be provided to augment some production facilities needed to handle the increased quantities of hardware that would be required, particularly the ET. The results of the NASA analysis are presented in Fig. III-2.

The three-year average shown for FYs 1986 through 1988, \$55.7M (1975 \$) formed the basis for the NASA pricing policy for this period. It currently appears that the NASA pricing policy after FY 1988 will be for full cost recovery rather than for only "out-of-pocket" costs, as in the FY 1986-1988 period; it has been viewed that the U.S. Government is essentially granting a subsidy of \$17.7M per flight (\$55.7M less \$38M) to commercial and foreign users in the FY 1986-1988 period. The NASA projections beyond FY 1988 show the annual average full cost per flight continuing to decrease as the flight rate builds up, decreasing in FY 1993 to \$46.4M for the 24-flight-rate model and to \$33.8M for the 40-flight-rate model. The importance of the increased flight rate in lowering the cost to the user is clearly evident. In the event that these cost projections are realized and the increased flight rate occurs, the non-government user in FY 1993 would be charged \$33.8M for a dedicated flight (M 1975\$) as contrasted to the \$38M (M 1975\$) per flight in the FY 1986-1988 period.



* TOTAL OPERATIONS COSTS - ALL COSTS INCURRED BY THE GOVERNMENT TO OPERATE THE SHUTTLE INCLUDING DIRECT AND INDIRECT

• CONSUMABLES - TOTAL OF ALL COSTS INCURRED BY THE GOVERNMENT FOR THE PROCUREMENT OF EXPENDED HARDWARE, REFURBISHMENT OF HARDWARE, ALL FLIGHT AND GSE SPARES, PROPELLANTS, PROVISIONS AND CONSUMABLES

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FIGURE III-1. Total operations cost elements (courtesy NASA)

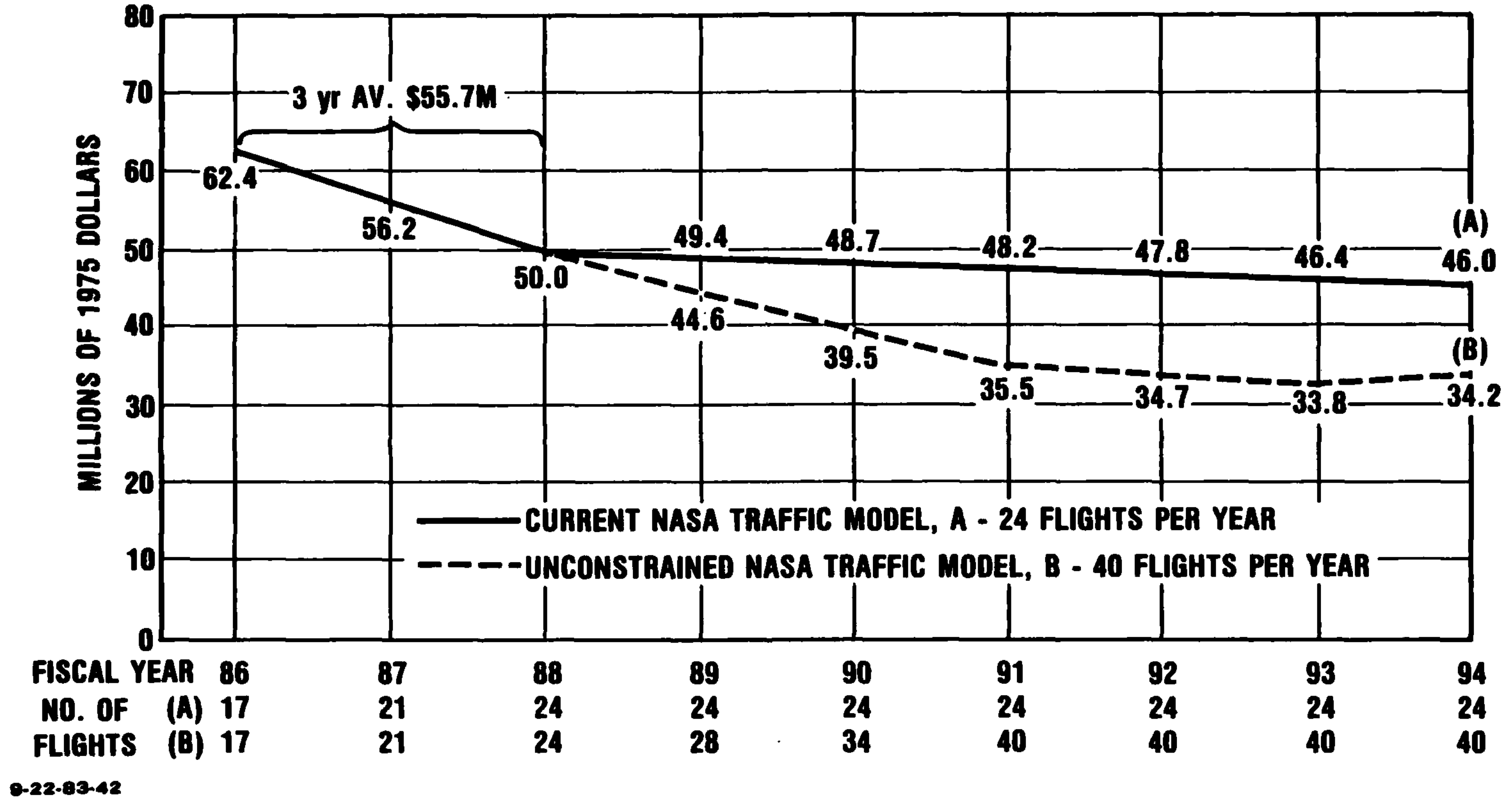

FIGURE III-2. Space Shuttle operations cost projections--
Average annual cost per flight (NASA source)

Some insight as to the reasons for the continuing decline in the annual cost per flight shown in Fig. III-2 can be gleaned from an examination of the cost trends associated with individual elements of the cost base (Table III-1). The elements in Table III-1 can be readily identified in the total operations costs diagram shown in Fig. III-1. Also tabulated in Table III-1 are the "Out-of-Pocket" costs and other charges that non-government users must pay in the FY 1986-FY 1988 period. Also tabulated are the items associated with the price per launch to the DoD in the same time period.

A digest of Table III-1 reveals that about 60 percent of the annual cost per flight--irrespective of year or flight rate--is directly traceable to the consumables, and that the principal contributors to that cost are the orbiter spares, the solid rocket booster, and the external tank. It is assumed that some learning criteria have been applied to these items that have helped in lowering costs in the outer years, but contract changes in the purchasing agreements for these items have also influenced the cost. These two influences have not been separated.

Items C, D, E, and F--costs associated with manpower allocations needed to carry out the operational functions--represent about 40 percent of the cost per flight. These items come close to representing the "Fixed" portion of cost per flight as contrasted to the "Materials and Services" elements which vary with the flight rate. It appears that no significant allowance has been made for "learning" in these categories, although it is reasonable to expect that decreases in manpower in some areas should develop as greater efficiency is realized over time and as turnaround tasks are streamlined and/or eliminated. It can be anticipated that additional reductions in the "fixed" portion of the cost should occur as experience is acquired in Shuttle Operations.

At the present time a "NASA/AF Memorandum of Agreement on Reimbursement of Launch and Associated Services for Users of the Space Shuttle" exists which stipulates the price to the DoD for Shuttle launches in the FY 1986-1988 time frame. This is the $29.8M per flight shown in Table III-1. A new agreement will have to be negotiated for launches after FY 1988. The details of such an agreement are under discussion, but at this time are in the "to-be-determined" (TBD) stage. However, it is encouraging that should

TABLE III-1. COST PER FLIGHT ESTIMATES--$FY 1975 (NASA SOURCES)

		3 yr. Average* FY 1986-1988	24 Flts/yr. FY 1993	40 Flts/yr. FY 1993
A.	Materials & Services			
	Orbiter Spares	$5.0	$3.7	$2.7
	Crew Equipment	0.5	0.4	0.4
	Main Engines	1.7	0.4	0.3
	Solid Rocket Booster	12.5	10.5	8.6
	External Tank	9.7	8.4	7.2
	Contract Administration	0.4	0.4	0.3
	Sub-Total	$29.8	$23.8	$19.5
B.	Propellants & GSE Spares			
	Propellants	1.0	0.7	0.7
	GSE Spares	0.7	0.6	0.3
	Sub-Total	$1.7	$1.3	$1.0
C.	Launch Operations Support (LOS)	9.5	8.5	5.3
D.	Flight Operations Support (FOS)	7.9	6.9	4.5
E.	Network Support	0.2	0.2	0.1
F.	Program Administration (R&PM)	6.6	5.7	3.4
	Total	$55.7	$46.4	$33.8
G.	"Out of Pocket" Costs			
	FY 1986-FY 1988 only			
			(Full-Cost-Recovery Policy)	
	Consumables - A&B	31.5	(25.1)	(20.5)
	Additive LOS	1.6	N.A	N.A
	Additive FOS	0.7	N.A	N.A
	Total	33.8		
	Contingency	4.2	N.A	N.A
	Price to Non-Govt User	$38.0	46.4	33.8
H.	Price to DoD (Item A Only)	$29.8	TBD	TBD

*Basis of NASA Pricing Policy.

item A in Table III-1 continue to be the principal cost item for the DoD, the increased use of the Shuttle by commercial and foreign users as well as U.S. Government users (the 40 flights per year rate) should result in a significant cost reduction for this item as estimated for FY 1993.

B. COST COMPARISON WITH EXPENDABLE LAUNCH VEHICLES

The specific delivery costs of candidate ELV GEO delivery systems, in dollars per pound of payload into GEO, were calculated and compared with similar Shuttle-based systems in IDA, 1982. The results were so lopsidedly favorable to the Shuttle that there seemed no justification for continuing any consideration of ELVs. In light of the continuation in interest in ELVs, however, and with the emergence of the new integral-propulsion-system (IPS) upper-stage concepts for the Shuttle, i.e., the TOS, the INTELSAT VI perigee stage (offloaded IUS SRM-1 as spinner), and the overloaded-SRM-1 concept, it seemed appropriate to review the former calculations to see if some misinterpretation had been made and to add the data for the new IPS perigee stages.

At this writing no new cost estimates for commercialized ELVs have been made available, so, for this review, a more careful scrutiny of previously available cost estimates was made, a more careful incorporation of the Shuttle cost dependence on load factor was included, and a correction to a more pertinent (to reasonable launch dates) common value of the dollar (FY 1986 dollars), using the latest extrapolation of BLS escalation factors (NASA, 1983a), was made.

The most carefully researched, consistently based cost estimates for ELVs that were available were from IDA, 1980, and represented business as it used to be conducted before the current commercialization endeavors; whether the commercialized ELV operations will be more or less costly than before is still not resolved, so the former costs will be used, and the strong dependence on production rate (which is another intangible) is ignored. Cost estimates for the TOS, IUS, Transtage, and Centaur vary from different sources and are given inconsistently as the same value for different year dollars, so we have arbitrarily (but based on available estimates) chosen FY 1986 dollar values. A summary of the cost assumptions for the different launch vehicles and upper stages is given in Table III-2, with the pertinent BLS escalation (inflation) factors extrapolated by NASA through FY 1987.

TABLE III-2. ADOPTED VALUES OF THE LAUNCH COSTS OF CANDIDATE LAUNCH VEHICLES AND UPPER STAGES WITH ESCALATION FACTORS TO CORRECT TO FY 1986 DOLLARS

Candidates	Launch Cost ($M)	Year of Dollars (FY)
Delta 3920	25	1980
Atlas/Centaur	52	1980
T34D	70	1980
Ariane	41.5	1980
PAM-D	3.0	1980
PAM-A	3.6	1980
Shuttle	38	1975
IUS SRM-1 (INTELSAT VI)	2.0	1982
TOS	20	1986
IUS	60	1986
Transtage	40	1986
Centaur	50	1986

Extrapolated BLS Escalation Factors (NASA, 1983a, November 1983)

Fiscal Year	Escalation Factor
1975	1.000
1980	1.515
1981	1.674
1982	1.818
1983	1.927
1984	2.033
1985	2.160
1986	2.303
1987	2.454

The resulting FY 1986 costs, the GEO payload, and the specific delivery costs into GEO for the different combinations are listed in Table III-3, and the specific delivery costs are plotted against GEO payload in Fig. III-3.

TABLE III-3. PERFORMANCE AND COST OF GEOSTATIONARY LAUNCH VEHICLES

Vehicle	GEO Payload (lb)*	Launch cost ($M-FY86)**	$K/lb
Delta/PAM	1,420	38 + 4.5	29.9
Atlas/Centaur	2,120	79	37.3
T34D/Transtage	4,100	106.5 + 40	35.7
T34D/IUS	4,100	106.5 + 60	40.6
T34D/Centaur	7,800	106.5 + 50	20.1
Ariane 1	2,160	63	29.2
2	2,760	63	22.8
3	3,280	63	19.2
4	5,340	63	11.8
Shuttle/PAM-D	1,400	18 + 4.5	16.1
/PAM-A	2,230	30.5 + 5.5	16.1
/offloaded SRM-1	4,800	44 + 2.5	9.7 (pair) 12.9 (one)
/TOS	6,800	80 + 20	14.7
/IUS	5,000	87.5 + 60	29.5
/Centaur G	10,600	87.5 + 50	13.0
/Centaur G'	14,000	87.5 + 50	9.8
/overloaded SRM-1	10,600	87.5 + 2.5	8.5
/overloaded TOS	10,600	87.5 + 20	10.1

*Using appropriate apogee-insertion propulsion system as required (per IDA, 1982).

**Does not include costs of apogee-insertion propulsion system (of the order of $5-10M) or of shrouds for expendables (of the order of $5-20M).

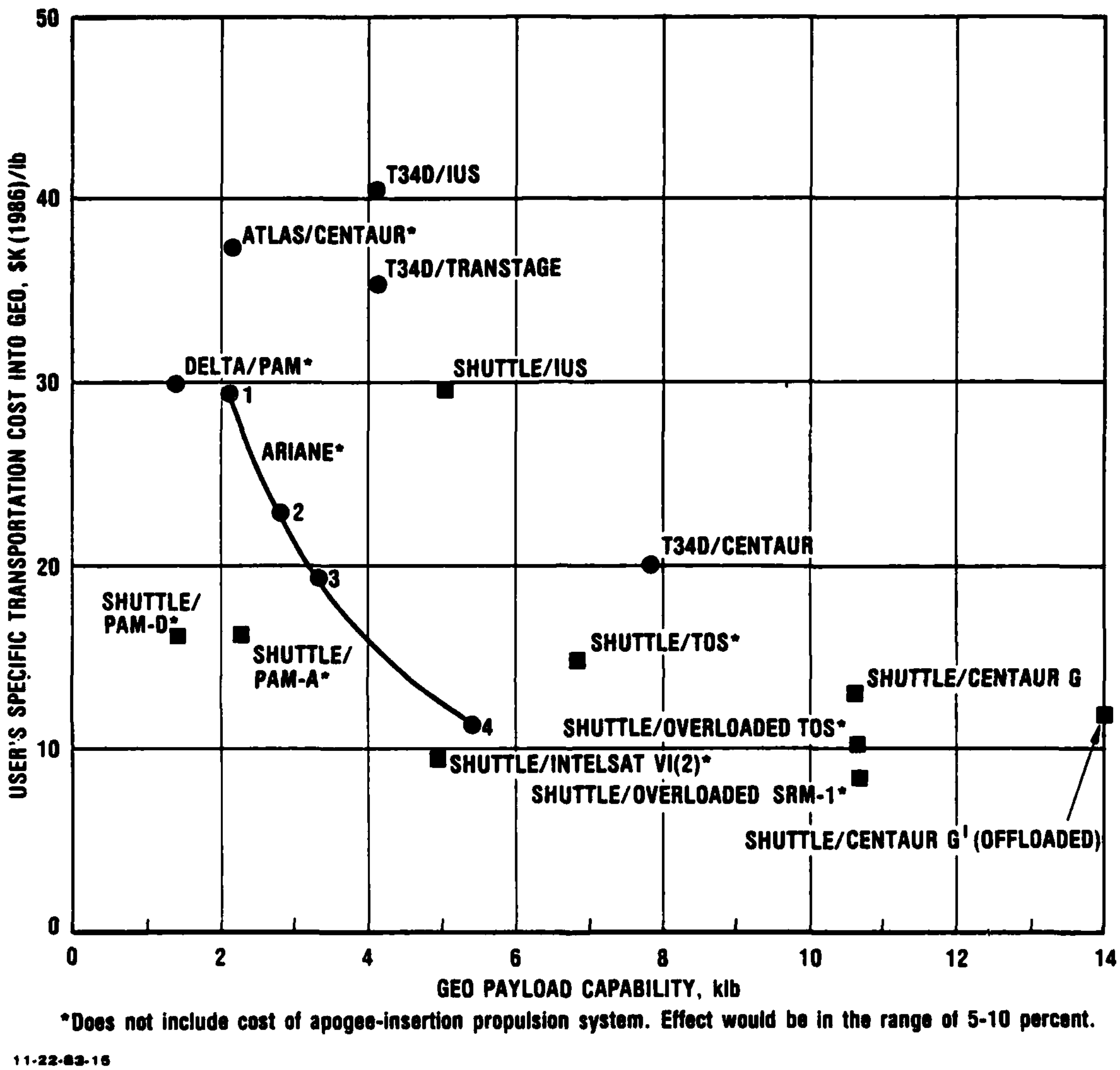

FIGURE III-3. Comparative specific delivery cost to GEO of different launch vehicles (post-1985 launch, FY 1986 dollars)

The results in Fig. III-3 are not noticeably different in character from IDA, 1982:

1. All ELVs (except Ariane 4) and the Shuttle/IUS are significantly more expensive in specific delivery costs than Shuttle-based competitors; the Delta/PAM and Atlas/Centaur are about a factor of two more costly than their payload equivalents, the Shuttle/PAM-D and the Shuttle/PAM-A.
2. The Ariane 4 achieves competitiveness by having the same (assumed) price as its progenitors. This assumption remains to be substantiated.
3. In the class of standardized upper stages the Centaur shows the greatest promise, provided it can be flown fully loaded to a single destination orbit, e.g., GEO.

The new indications from the figure are that the various perigee-kick stages from the PAMs through the IUS SRM-1 versions are quite competitive with the versions of the Centaur in specific delivery costs (assuming the cost for integral propulsion is absorbed in the payload), and promise greater flexibility in lower launch cost for partial payloads to different destination orbits. The perigee stages with IPS also should make more efficient use of the Shuttle cargo volume with their greater density.

C. INTEGRATION (AND OTHER LAUNCH-RELATED) COSTS

IDA, 1979, included a summary of the results of a study conducted by USAF (SAMSO) of payload integration and other related launch costs for a typical single complex payload mated to an IUS and launched on the Space Shuttle. At the time of the study, many assumptions had to be made regarding the nature and extent of the integration tasks required, inasmuch as neither the spacecraft nor the IUS existed--and the Space Shuttle had not yet flown. Since that time, a Tracking and Data Relay Satellite (TDRS)--a complex spacecraft of the kind considered in the USAF study--has been mated to an IUS and the composite payload successfully launched into a low earth orbit by the Space Shuttle. The nature and cost of the payload integration activity associated with that mission (TDRS-A) has been furnished IDA by NASA (NASA, 1983b) along with similar estimates for the two remaining spacecraft (TDRS B and C) to be launched in the future. In the following sections, an attempt is made to relate the findings of the 1979 USAF study with the data for the first TDRS launch to appreciate more fully the task of estimating reliably the costs of payload integration.

1. DoD Spacecraft Integration Costs -- 1979 USAF Estimates

Figure III-4 details the breakdown, from the 1979 USAF study, of the estimated STS delivery costs for a typical DoD spacecraft undergoing first-time integration to an IUS for a Space Shuttle Launch. The crosshatched segments--labeled STS Launch Charge and IUS Flight Vehicle--pertain to Shuttle launch costs and IUS procurement and flight operations, neither of which is part of the integration cost. They will not be considered further except to say that the manpower effort and costs associated with these items have changed markedly in the years since the study and as of now will reflect different percentages of the total delivery cost from those shown on the figure. However, the man-months of effort and costs associated with the other items on the chart (the integration activity) should still be comparable with the effort for similar tasks required for the TDRS. Table III-4 lists the estimated costs for integration services specified by the segments of Fig. III-4 in the 1979 dollars used in the study and in 1983 dollars (using a BLS cost escalation factor ratio of 1.397, i.e., 1983 BLS factor/1979 BLS factor) (1.927/1.379 = 1.397).

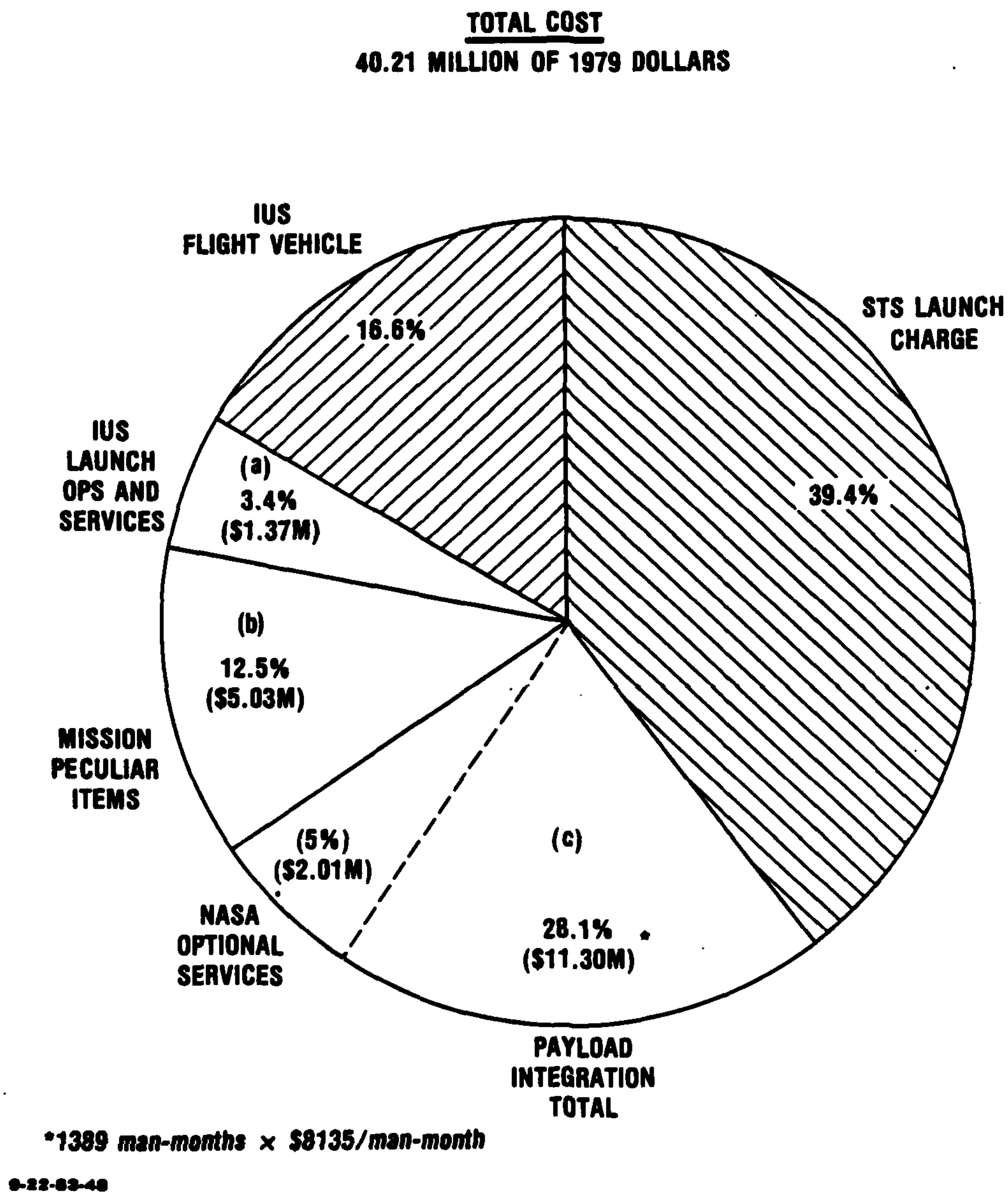

FIGURE III-4. STS delivery cost--typical DoD spacecraft (Courtesy USAF). Based on chart from IDA, 1979

TABLE III-4. LAUNCH-RELATED SERVICE COSTS--USAF STUDY (Data from Fig. III-4)

		Estimated Costs	
		1979$	1983$*
(a)	IUS Launch Operations and Services	1.37M	1.91M
(b)	Mission-Peculiar Items (hardware and services)	5.03M	7.03M
(c)	Payload Integration Total (NASA Optional Services)	11.30M (2.01M)	15.79M (2.81M)
	TOTAL		24.73M

*1979$ x 1.397

Item (a) includes all activity associated with the processing of the IUS at KSC. Item (b) is split about equally between IUS hardware (kits and software modifications) and KSC support and services not costed under item (c). Item (c) is the largest contributor to the payload-related costs and includes all of the effort associated with the analytical and physical integration of the spacecraft onto the IUS and the Shuttle, including supplementary and auxiliary analyses such as provided by the Aerospace Corporation and/or others depending on the USAF Space Division Commander's decision requiring independent validation of certain interface analyses (e.g., loads, software, stability and control).

Item (c) also includes the cost of NASA optional services. At the time of the study, uncertainties existed as to what constituted "NASA Standard Services" (included in the basic launch cost) and what should be regarded as an "optional" service to be paid for separately. NASA and USAF have since resolved many of the uncertainties in question and the definition of both Standard and Optional Services is detailed in a jointly prepared "Memorandum of Agreement on Reimbursement of Launch and Associated Services for Users of the Space Shuttle." NASA agrees to undertake any reasonable optional services that DoD can define and that NASA can capably perform. Each such optional service for a particular payload is scoped technically and the cost estimated in a Payload Integration Plan (PIP). Upon receipt of funds from the user, the service is implemented. It is anticipated that some operational service items, once developed and implemented, will become "standard" services for subsequent identical use.

A substantial portion of the costs in item (c) and some in item (b) are related to the serial time that was estimated to be required on the launch pad at KSC when the "Factory-to-Pad" assembly scheme was planned for DoD payloads. Since then, the USAF has modified the Solid Motor Assembly Building (SMAB) at KSC to allow for off-line processing of payloads, including assembly and checkout, prior to installation at the launch pad (IDA, 1980). We believe, therefore, that the costs currently associated with these items might be significantly lower than shown in the table.

Actual costs incurred are difficult to pinpoint precisely in constant dollars because the charges for launch-related activities stretch over a period of years--a four-year integration cycle is typical. Payments are made in real-year dollars at the time the service is performed.

2. TDRS Spacecraft Integration Costs--1983 Actual

Table III-5 summarizes the Launch Services Agreement (LSA) costs of various tasks associated with the analytical and physical integration of the TDRS spacecraft onto an Inertial Upper Stage (IUS), and the subsequent integration of the assembled payload into the Shuttle Cargo Bay.

The costs for TDRS-A (launched from the Shuttle April 15, 1983) are the updated (actual) costs assessed to the program by NASA as of April, 1983. The corresponding items for TDRS-B and C (also updated as of April, 1983) include both actual and estimated runout costs inasmuch as the payment period for various services and hardware extends back to 1978. Before commenting further on the chart, a brief explanation concerning the origin and nature of the LSA may be helpful in understanding the nature of the updating process.

When NASA undertakes a contract with a user--in this instance the Space Communications Company (Spacecom)--the user forwards his requests for Services to NASA where they are incorporated into a Payload Integration Plan (PIP). This is a dynamic process extending over a period of years

TABLE III-5. LAUNCH SERVICES AGREEMENT (LSA) COSTS--GOVERNMENT ONLY
(Millions of real-year dollars)

	TDRS-A	TDRS-B	TDRS-C
Upper Stage (927)[1]	LSA Update	LSA Update	LSA Update
o Two-Stage IUS (including SD/PIC charges)*	(25.1)	(27.1)	(23.5)
o IUS Processing/KSC	2.4	2.3	2.2
o Flt. Ops./JSC	1.0	0.9	1.1
Payload Support (928)[1]			
o Mission-Peculiar Items	2.8	0	0
o Analytical Int.	11.5	4.3	3.1
(SINC/JSC)**	(5.6)	(3.3)	(3.1)
(Cont. Mis. Plan/JSC	(3.5)	(-)	(-)
(IV&V/MSFC)***	(1.9)	(1.0)	(-)
(Alt. Flt. Design/MSFC)	(0.5)	(-)	(-)
TOTAL (Launch-Related Service Costs Only)	17.7	7.5	6.4

[1]Budget Code Numbers.

*Space Division/Payload Integration Contractor.

**Spacecraft Integration Contractor/Johnson Space Center.

***Independent Verification and Validation Contractor/Marshall Space Flight Center.

during which the user can at any time add or subtract from his requests. For example, the user may not realize he may require more time at the Kennedy Space Center to prepare his payload or may require more space to service the spacecraft. Also, mission-peculiar items may be required that were not anticipated by the user at the beginning of the 4-year activity cycle.

The identification of all services and hardware items that should properly be categorized as "integration" activity is made difficult by the way in which many of these activities are contracted for. For instance, some of the integration costs are submerged in the procurement costs of the TDRS. For example, the two-stage IUS procurement cost of $25.1M (the DoD charge to NASA) includes a Payload Integration Contractor charge that is not easily identified because of the way in which the Space Division (USAF) has contracted for this kind of activity. Boeing has a contract with the Space Division to carry out the analytical integration of fifteen spacecraft to the IUS of which the TDRS-A is only one. The contract does not spell out in detail how much effort is to go on each individual spacecraft.

The most costly item in Table III-5 (apart from the cost of the upper stage itself) pertains to the principal analytical integration activity. It is of significance that the charge for this activity for future launches of the same payload (i.e., TDRS-B and C) drops to 37% and 27% of the TDRS-A charge of $11.5M. The item identified as IV&V (Independent Verification and Validation) is a requirement imposed by the Space Division on a user procuring an IUS. This charge--about 17% of the total analytical integration cost--is one that the user would not have to pay if the Space Division Commander would relax his policy of requiring this independent analysis for flight readiness. In time, it is likely that this requirement will be dropped with a consequent reduction in user costs for payload integration. It should be noted also that mission-peculiar items procured for TDRS-A can be used for follow-on flights.

Regrouping the items in Table III-5 in an attempt to match the items in Table III-4 results in Table III-6. A comparison of these tables shows that the cost of IUS launch operations and services experienced by TDRS-A ($3.4M) is considerably higher (78%) for this item than that estimated in the 1979 USAF study whereas the mission-peculiar items for the TDRS-A are lower in cost by 60%. (Considerable caution must be exercised on this item, however, because it is very spacecraft-dependent.) Also, as mentioned earlier, "Factory-to-Pad" considerations cloud the USAF study estimates.

It is evident that the major cost item in both cases is Payload Integration. This fact was correctly predicted in the USAF Study, albeit the estimate obtained in the study is about 37% higher than the TDRS-A actual cost. It is worth noting that the total Launch Related Service Costs for the TDRS-A ($17.7M) is about 40% lower than the corresponding figure for

TABLE III-6. TDRS-A LAUNCH-RELATED SERVICE COSTS
(Data from Table III-3)

	Actual Costs (Real Year $'s)
(a) IUS Launch Operations and Services	$ 3.4M
(b) Mission-Peculiar Items (hardware and services)	2.8M
(c) Payload Integration (including optional services)	11.5M
TOTAL	$17.7M

the USAF Study ($24.73M)--an encouraging result considering that the TDRS-A is the initial experience in mating a large complex satellite to the Shuttle. It is also significant, as Table III-5 documents, that the total Launch-Related Costs of repeat launches of the TDRS satellite are expected to be of the order of 60% less than for TDRS-A. While these estimates are probably no longer valid in the precise amount shown because of delays in the TDRS program, there is every indication, nevertheless, that very substantial savings in launch-related service costs will occur in repeat launches of identical or similar satellites.

3. DELTA Class Payloads

The preceding discussion dealt with the integration of a single large payload to the Shuttle. A large number of Shuttle flights in the next few years, however, will be carrying several smaller spacecraft on each flight. The integration activity involving smaller spacecraft, while less extensive than for the TDRS-type spacecraft, is no less demanding and must be implemented with equal care. Shuttle flight STS-5 carried two of this smaller, DELTA-class spacecraft, each mated to a PAM-D, and furnishes an opportunity to examine the nature and costs of the integration activity typical of this class payload.

The two satellites flown on STS-5 were the SBS-C and the Telesat-E (Anik). A listing of the optional services requested of NASA by the two users is given in Table III-7 along with information relating to the NASA organization supplying the service and the estimated charges for the services.

As is evident from the Table, the nature of the optional services requested by the two customers was quite similar although some differences in charges will be noted--especially in the communications area, where the SBS-C user requested tracking information on the PAM-D stage whereas the other user did not. This was a one-time activity and probably will not be repeated for a subsequent launch of the SBS series. Similarly, the Shuttle Avionics Integration Laboratory (SAIL) tests at JSC are usually a one-time activity carried out on the initial spacecraft of a series. Generally, customers with similar requirements can take advantage of tests performed on another's spacecraft of a similar type. For example, a SAIL Test was deemed unnecessary for the SBS-C inasmuch as this customer was able to use the information obtained on the Telesat-E. Otherwise, the charges are quite similar and are of the order of $1.4M in real-year dollars. The price of a 1983 Shuttle launch for a Delta class payload in real-year dollars is about $14M (IDA, 1982), to which must be added the price of PAM, about $5M. Thus, the total cost of integration and optional services for the DELTA-class payload for a first flight would be less than 10 percent of the launch cost. Repeat flights of an identical payload should be less as some services are dropped. Detailed information for making a complete comparison does not as yet exist, but should become available following the launch of Telesat-F and SBS-D on STS-15 (flight 41-F by the new nomenclature) currently scheduled for June 12, 1984.

D. IMPACT ON SHUTTLE COST FROM A CHANGE IN COMMERCIAL UTILIZATION

We have examined the potential impact on the cost to the U.S. Government of its use of the Shuttle that might result from a change in the number of commercial and foreign users of the Shuttle, i.e., a change in the number of flights beyond the basic national traffic in the FY 1986-88 time period.

TABLE III-7. USER OPTIONAL SERVICES--STS-5

Optional Service Description	Charging Method	Cognizant Center	Estimated Charge (rounded amounts) SBS-C	Teleset-E
SAIL[a] Test	G.C.[1]	JSC	N.A.	$139,500
Initial Telesat Spacecraft Launch Site Support Package	F.P.[2]	KSC	$718,000	720,000
Initial SSUS, PAM-D Launch Site Support Package	F.P.	KSC	179,000	179,000
SSUS-D Amortization	F.P.	NASA Hq.	50,000	50,000
24-Hour Security	G.C.	KSC	Cancelled	27,000
Communications Services/GSFC	G.C.	GSFC	92,500	18,000
End-to-End Tests in CITE[b] and the Pad	F.A.	JSC	94,000	94,000
Post-Flight Data	G.C.	JSC	3,000	1,500
PAM-D SC Failure & Recovery Impact	G.C.	KSC	105,000	105,000
TOTAL			$1,241,500	1,334,000

NOTES

[1]Government Cost (actual).

[2]Fixed Price--Negotiated.

[a]Shuttle Avionics Integration Laboratory.

[b]Cargo Integration Test Equipment.

If the number of flights in a given period changes, the cost per flight can change through three principal avenues: (1) the manpower required to carry out the launch and flight operations should change in the same sense as the traffic change, but more slowly, (2) the change in production rate of expendables should change the efficiency of usage of production facilities and, therefore, inversely the unit cost, and (3) the total number of expendable elements purchased will change and the variation in average cost due to learning over a different number will change the average cost oppositely to the change in number.

1. Cost Assumptions

a. In the FY 1986-88 pricing policy, the "additive" costs of manpower to support all non-U.S.-Government Shuttle flights beyond the basic manpower requirements for the NASA/DoD program are charged to the user. So, there should be no impact on the basic U.S. Government operations costs from any change in the number of commercial and foreign flights in the FY 1986-88 period. (If "full" cost recovery, per Table III-1, is adopted as the pricing policy after FY 1988, the non-Government user would pay a pro-rata share of the total operations costs, which are the sum of the basic operations costs for a U.S. Government flight and the "additive" costs for the non-Government flight. In the case of one non-Government flight, the annual cost of the U.S. Government program for n Government flights would be reduced by an amount equal to the total operations costs divided by n + 1.)

b. The available cost projections for production of expendable components, e.g., the external tank, show no dependence on production rate, only total number produced, with the reduction with increased number assumed to be described by a learning curve. The calculations here of the impact of a change in the number of commercial flights ignore a production-rate dependence.

c. The reduction in unit cost of the external tank with increasing number produced has been described by MSFC as following an 84 percent learning curve. For SRB refurbishment, with its costs depending more on replacement of materials, such as the solid propellant, rather than on labor-intensive fabrication, a slower learning rate (than for the ET) is to be expected. We assume a 95 percent learning curve for SRB refurbishment, consistent with data on solid-rocket production assembled in the IDA Reusable Launch Vehicle Study of 1964-66. With the assumed learning rates, we calculate two cases of the impact of commercial flights on the costs of the U.S. Government flight program: (a) the addition of one or more Shuttle flights, and (b) the elimination of all ELV-compatible non-DoD flights. The flight numbers and costs are taken from the FY 86-88 traffic projection and the FY 86-88 pricing policy. The Mission Model of January 1983 describes 65 flights from STS-5 through the end of FY 87 and indicates that about one-third would be ELV-compatible non-DoD flights. The traffic projected for FY 86-88 starts with the 33rd flight and ends with the 94th flight, for a total number of 62 flights. The data used in setting the pricing policy give the cost of an ET as $9.7M and the cost of a pair of SRBs as $12.5M, assumed here to be the average costs for the 62 flights in the period.

2. Calculations

a. One more Shuttle flight. If an extra Shuttle flight in the FY 1986-66 period is sold to a commercial or foreign user, the cost of the additional ET and SRBs will be less than the average by an amount specified by the learning curves. If the customer pays the average cost stated in the pricing policy, the U.S. Government will realize a "profit" of the difference. Using the formula

$$\bar{C} = \frac{C_1}{(N_2-N_1)(1+a)}\left[(N_2+\frac{1}{2})^{1+a} - (N_1+\frac{1}{2})^{1+a}\right]$$

where $\bar{C}$ = average item cost (=$9.7M for ET and $12.5M for SRBs)

C_1 = first item cost (unit ET or pair of SRBs)

N_2 = 94

N_1 = 32

a = log LRN/log 2

LRN = 0.84 for ET and 0.95 for SRB,

the derived values of C_1 to give the assumed average costs are

C_1 = \$27.179M for ETs and \$16.936M for SRBs.

The cost of the 95th ET is calculated as \$8.646M and that for the 95th pair of SRBs is \$12.091M for a sum that is \$1.462M less than the sum of \$9.7M and \$12.5M. (Note: The precision of the values given here is mathematical, not real.)

b. Elimination of all ELV-compatible non-DoD flights. If 20 (say) of the 62 Shuttle flights projected for FY 1986-88 are dropped because the payloads transfer to ELVs, the average cost to the U.S. Government for the remaining 42 will increase. The average cost of the 33rd through 74th ET becomes \$10.0754M and of the 33rd through 74th pair of SRBs \$12.6434M. The increase in average cost over the \$9.7M plus \$12.5M for the full schedule becomes \$0.5188M; the increase for 42 items becomes \$21.7896M.

3. Recapitulation

If an extra Shuttle flight in the FY 1986-88 period is sold to a commercial or foreign user for the established price, the difference between the cost of the additional ET and SRBs and the price paid for them gives the U.S. Government a "profit" of about \$1.5M.

If 20 Shuttle flights in the FY 1986-88 period with ELV-compatible payloads are lost to ELVs, the average cost of the remaining ETs and SRBs will increase, causing a total increase in cost to the U.S. Government of about \$21.8M spread over the three-year period, an average increase of about \$1.1M for each Shuttle flight lost.

(For "full" cost recovery after FY 1988, the U.S. Government could gain an annual cost savings of the order of \$19M for each non-Government flight if basic annual U.S. Government operations costs are the order of \$400 M and the basic annual U.S. Government traffic is 20 launches.)

E. TURNAROUND-REDUCTION EFFORTS

IDA, 1982, treated at length the constraints to the Shuttle flight rate due to turnaround servicing operations and production limitations and highlighted the importance of flight rate in affecting the cost per flight.

NASA recognizes the importance of turnaround operations in influencing launch costs and is placing heavy emphasis on ways and means of effecting a reduction in turnaround time. During the current year KSC established an ad hoc Turnaround Reduction Study Group to address this issue. A synopsis of the results of the activity of this group presented to IDA (KSC, 1983) is given in the following paragraphs:

In early 1982 the senior planning personnel at KSC reviewed the progress in reduction of turnaround time achieved for the first four flights of the Shuttle and compared it with the concurrent rate of growth of the assessments of the Shuttle Turnaround Analysis Group (STAG) for the turnaround time to be expected for mature operations. They found that the rate of decrease of actual experience and the rate of increase of the STAR/STAG assessments indicated a potential crossover within the next few flights, at which time the actual interval between flights could be less than the interval projected to be required for "mature" operations, regarded as starting approximately with STS-30, i.e., after FY 1985. This potential excess of estimate over achievement led to a conclusion that the methodology of producing turnaround assessments used by the STAR/STAG organization was inadequate, so a new ad hoc group with greater hardware/operations orientation was convened for the period June-September 1982 to review the issues of turnaround reduction.

The charter of the ad hoc Turnaround Reduction Study Group was to go beyond simple extrapolation of current practices (as previously done) and to determine means to make drastic reductions in servicing operations. New approaches considered were in two principal directions: (1) measuring operating limits more exactly so that unnecessary conservatism in servicing and safety precautions could be identified and eliminated, and (2) reconfiguring servicing-facility elements and Shuttle components to facilitate maintenance and checkout operations. Some cited examples of (1) were the following:

(a) The RCS engines had not been qualified for ingestion of gas with the propellant fluid, so the RCS manifold had to be pumped down to vacuum, a time-consuming process, before introduction of propellant, to assure a liquid-only flow. A test program was initiated that showed that the engine suffered no damage from ingestion of gas/liquid mixtures, and the vacuum-pumping operation could be safely eliminated from servicing procedures.

(b) The laminated composite structure of the OMS-pod covers was subject to absorption of moisture that could turn to steam during reentry heating and cause structural damage. On this basis, the OMS-pod covers have been baked out on the pad before flight, involving installation of special heaters and blankets and about 9 days of drying time. The proposed solution was to reappraise the requirements for reentry attitudes that might produce excess temperature and add insulation to reduce the temperature. It was found that the requirement for the marginal reentry attitudes was so infrequent in the early flights that the dry-out operation could be eliminated most of the time, and the excess heating in the infrequent case later was small enough so that addition of insulation to the design of OV-103 pod covers (retrofitable to OV-102/099) would reduce the temperature to a safe level, making bakeout unnecessary.

(c) Refilling the APU fuel tanks after a flight required complete evacuation and refilling with a measured quantity of fuel. It was established that the ullage pressure of the tank after the first measured filling could be used to gauge the completeness of subsequent fillings, so that the complex evacuation and weighing operations could be replaced with a much simpler topping-off and pressure-measurement process.

Some cited examples of (2) were the following:

(a) The stacking and closeout of the SRB assembly on the MLP in the VAB highbay was estimated in STAR 21 to involve as much as 23.5 working days. A significant contributor to the serial time was assembly of the cableway on the side of each SRB. The cableway is fabricated of many small cover segments that must be attached with many screws, and sealed with gasketing and paint against intrusion of moisture and sea water. A design suggestion currently under review is to replace the cableway and cover with a preassembled cable harness presealed in a cylindrical tube that would be mounted simply by brackets to the side of an SRB.

(b) When the Orbiter is brought into the OPF cell, it must be leveled at the height of the work platforms. This process currently involves moving the overhead crane into position, attaching lifting hooks to special fittings on hard points on the sides of the Orbiter, clearing the area, and lifting the Orbiter so that portable jackstands can be placed under it. The suggested improvement is to install hydraulic lifts in the floor under the footprint of the landing-gear wheels, like those for automobiles in service stations, that can raise the Orbiter directly for the jackstands, dispensing with special attachments and their extra safety precautions.

(c) After the Orbiter has been wheeled into the VAB, it must be lifted and the landing gear raised so that the Orbiter can be attached to the Shuttle vehicle stack. Currently, raising the landing gear requires starting up the Orbiter's APU and powering-up the Orbiter's control system, a complex and time-consuming process. Addition of T-connectors to the electrical and hydraulic lines accessible through existing openings in the Orbiter is proposed to allow use of external electrical and hydraulic power to raise the gear without activating Orbiter systems.

These examples are our interpretation of some of the more significant changes under consideration, but there are literally dozens of lesser operational and hardware changes that have been recommended or have already been implemented. The total cost to implement the hardware changes is estimated at about $1.6M.

While the reduction in serial time for each of the individual improvements was not specified, the cumulative effect was stated to give a reduction in turnaround time to 22 three-shift working days (or a corresponding reduction in work force if the mission manifest does not require this flight rate). The marked change with this reduction is shown graphically in Fig. III-5*, in comparison with STS-4 as run and with a flight representing the assessment in STAR 23.

The new processing times for each major operation are listed in Table III-8 in comparison with values from STAR 21 (9/29/81) and STAR 23 (5/12/82),

*23-day turnaround discussed later.

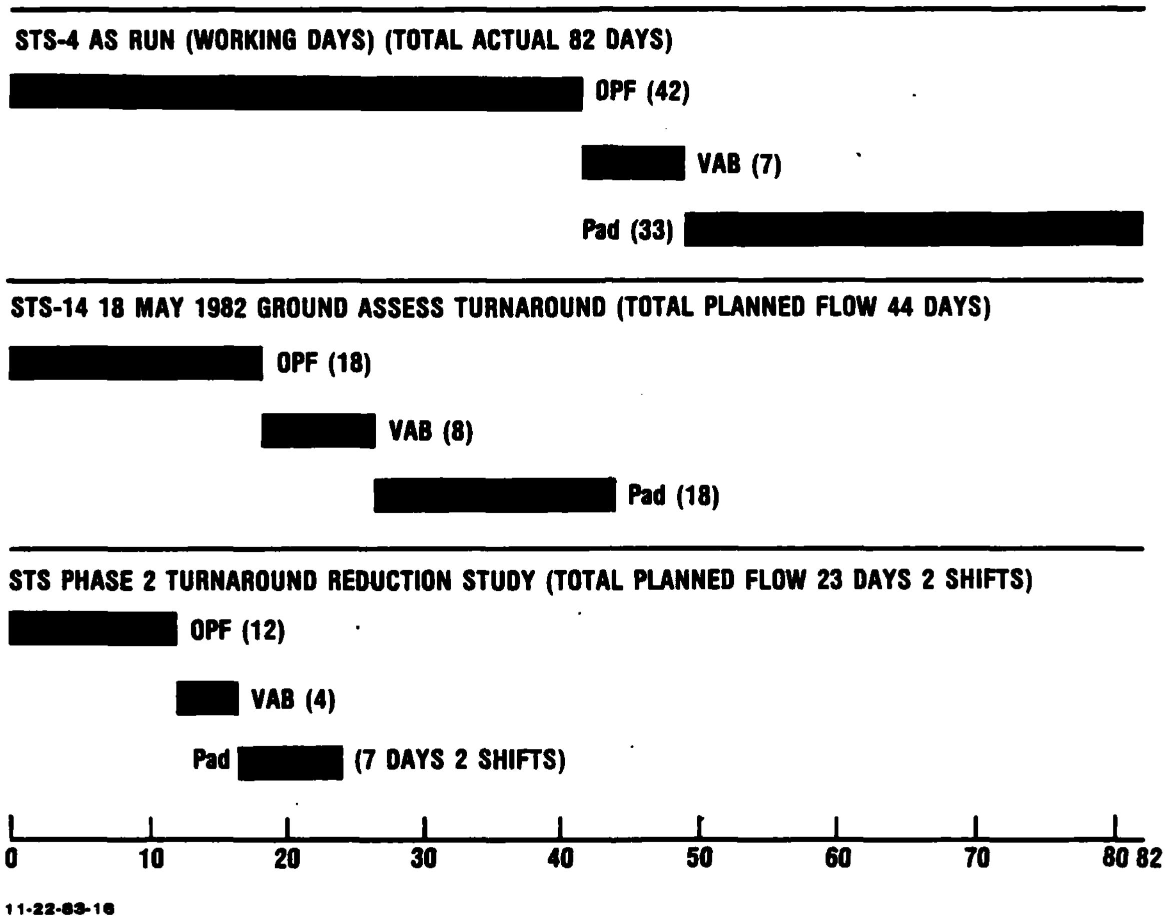

FIGURE III-5. STS turnaround reduction study (from KSC, 1983)

TABLE III-8. EVOLUTION OF TURNAROUND-TIME COMPONENTS AND FLIGHT RATE

PROCESSING TIMES (3-shift working days)

	STAR 21	STAR 23	Ad Hoc KSC Study
Orbiter in OPF	8.3	16.7	12
Pad refurbishment	5	5	4
MLP refurbishment	4.2	4.2	1 (in VAB)
SRB/ET assembly	34.5	16.3	7
Orbiter mate	4.1	7	5
Checkout on Pad	6	13.3	5

TOTAL OCCUPANCY TIMES (3-shift working days, rounded to next higher integer)

	STAR 21	STAR 23	Ad Hoc KSC Study
Orbiter (incl. 5-day flight)	25	43	28
OPF cell	9	17	12
MLP (VAFB Pad)	49	42	19
VAB HB	39	24	13
Pad (incl. 1-day weather hold)	12	20	10

THEORETICAL MAXIMUM FLIGHT/YEAR FOR ONE OF EACH ELEMENT

	(7-day wk)	(7-day wk)	(5-day wk)
Orbiter	14.6	8.5	9.3 (8.6)*
OPF cell	40.6	21.5	21.8 (18.2)
MLP (VAFB Pad)	7.5	8.7	13.7 (12.2)
VAB HB	9.4	15.2	20.1 (19.0)
Pad	30.4	18.2	26.1 (21.0)

*KSC figures in parentheses, assume 2-shift days on Pad.

together with total occupancy times for the five major elements and the theoretical maximum evenly-spaced flight rate that could be supported by one of each element. In Fig. III-5 the time on the pad is lengthened due to the assumption of two-shift rather than three-shift days and the time for Orbiter mating in the VAB is shown as 4 days rather than the 5 in Table III-8, so that the total planned flow is shown as 23 days rather than 22. In Table III-8 we add a 5-day flight time and a 1-day weather hold on the Pad to give an Orbiter launch-to-launch time of 28 days. The theoretical maximum annual flight rates in Table III-8 are calculated, for a 7-day work week, by dividing 365 days by the occupancy times, and, for a 5-day work week, by dividing 261 days by the occupancy times. The KSC Study Group flight rates for the 5-day work week (in parentheses in Table III-8) are smaller chiefly because they assume two-shift working days on the Pad rather than three. With the flight rates for 5 three-shift days per week, the planned numbers of each element could support the following maximum annual numbers of flights:

Element	Maximum Annual Flights
4 Orbiters	37.3
2 OPF cells	43.6
3 MLPs	41.1
2 VAB HBs	40.2
2 Pads	52.2

And if the occupancy time of the VAFB pad is the same as that of an MLP, the VAFB Pad could sustain a maximum theoretical rate of 13 flights/year. The planned numbers of the major elements should therefore all support the maximum targeted projected flight rate of 40 per year, with the exception of the four Orbiters at 37.3 flights per year. Of course, simplistically, an increase in work week from 5 to 6 days should increase all these numbers by 20 percent, so a surge capability to flight rates upwards of 45 per year may be possible without increasing the planned numbers of elements.

With gradual implementation of the "revolutionary" changes recommended by this ad hoc group (some to be available in time to help recoup the schedule delay from postponement of STS-6), it was projected by the group that the turnaround-time reduction to 22 working days should be achievable as early as flight STS-21, when the last of the currently envisioned changes is planned to be in place. It is of interest to compare this potential capability with the turnaround-time requirements assumed in constructing a late mission manifest (August 15, 1983) which covers the scheduled dates of flights through the end of FY 1988, i.e., through flights STS-81 and 11V. From differencing the scheduled launch dates for individual orbiters one gets the launch-to-launch intervals in calendar days. Subtracting the flight durations and multiplying the remainder by 5/7 gives the turnaround interval in working days, assuming a 5-day work week. The results are plotted versus flight number in Fig. III-6. Included in the figure is the projected 22-day turnaround-time floor starting at flight STS-21.

The turnaround-time points plotted in Fig. III-6 for KSC flights and VAFB flights show no marked "learning" trend, scattered almost randomly between 29 and 59 days for KSC and between 39 and 115 days for VAFB. The later (FY 1987-88) times clump around 35 working days, almost a factor of two above the possible 22-day capability. Thus, the launch-processing capability may exceed the demand by almost a factor of two. In other words, even if the demand were to grow by as much as a factor of 35/22 one would have to look elsewhere than KSC to find flight rate limits ("choke points"), such as those that might be imposed by ET production rate or SRB refurbishment time. The NASA Administrator, in testimony reported in Aerospace Daily, March 28, 1983, stated that (quoting Aerospace Daily), "NASA will need about $470 million over the next four years to build additional production facilities for Space Shuttle external tanks and solid rocket boosters in order to reach a flight rate of 24 per year." Further, it was said that, "if NASA were to fly 40 missions per year ... another $2 billion would be needed-$500 million for facilities and $1.5 billion for a fifth orbiter."

F. NOMAD STAFFING FOR VAFB LAUNCHES

The McDonnell Douglas expendable launch vehicle Delta is launched out of ETR and WTR. McDonnell Douglas is the launch contractor and maintains

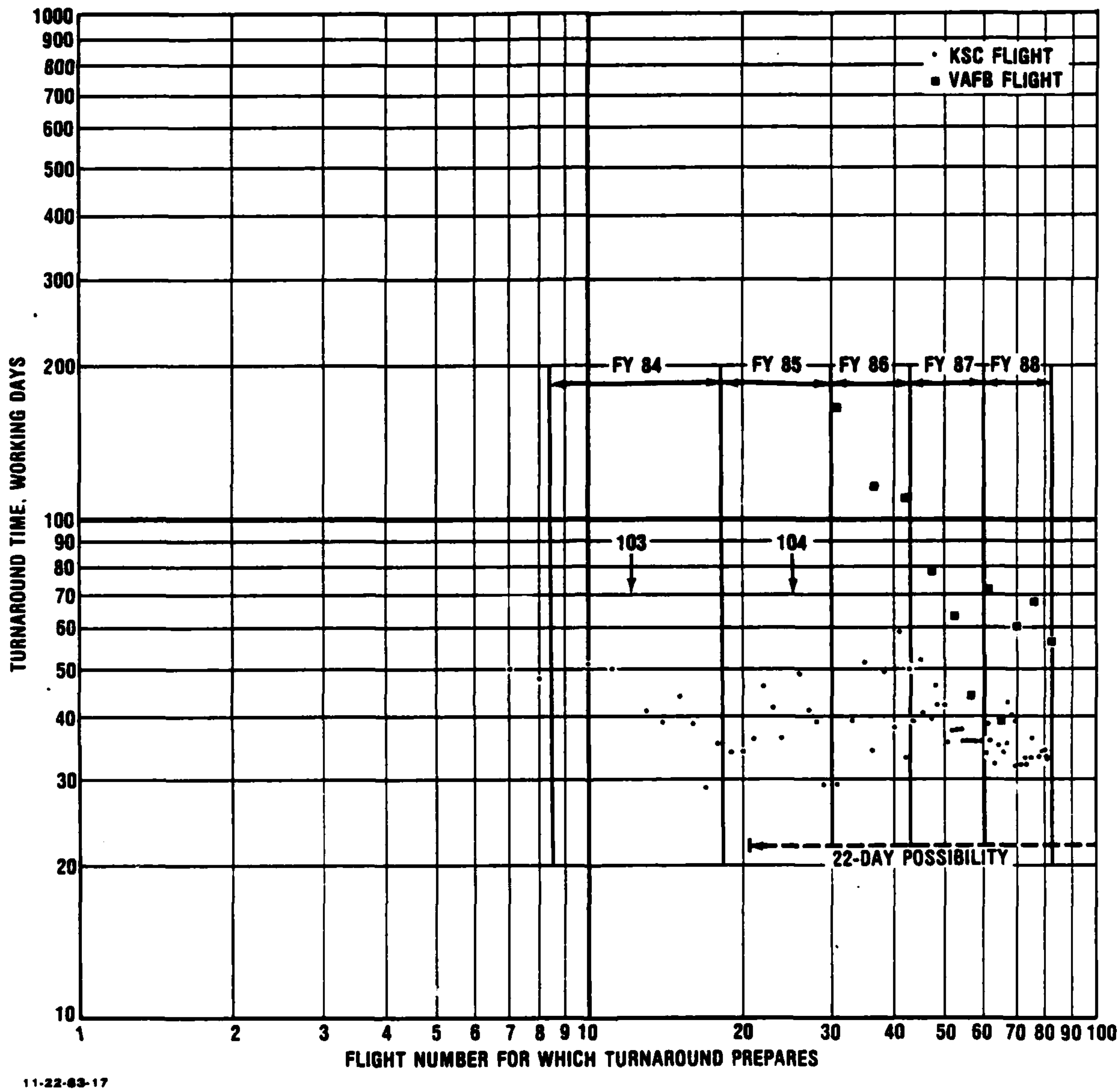

FIGURE III-6. Turnaround-time evolution assumed in 8/15/83 flight schedule a mobile team of 230 people at the Cape Canaveral launch site where most of the launches take place. A skeleton crew of 13-15 people is stationed at VAFB. When firings take place at VAFB some of the mobile crew at ETR are temporarily assigned there. Simultaneous launches at both sites are not possible with the current staffing.

The crew contains a mix of disciplines--solid rocket technicians, guidance and control experts, etc. Some are multiple-trained to perform various tasks while others serve a single function.

The Kennedy Space Center manages the Delta vehicle for NASA and supervises the MDAC launch team. KSC personnel assigned to this task number about 40 at ETR and about 6 at VAFB. The use of nomad crews for ELV launches raises the issue as to whether Shuttle launches at VAFB might similarly be served by launch crews stationed at KSC, especially in the early years of VAFB operations when the frequency of Shuttle flights is low. This now appears to be a realistic possibility with the introduction of the Shuttle Processing Contractor (Section III-G), whose responsibilities include launch operations at both KSC and VAFB. Inasmuch as the SPC Contractor has overall control of the manpower utilized in launch operations at both sites he is in a position to transfer crews between KSC and VAFB as the launch schedule requires.

G. SHUTTLE-PROCESSING-CONTRACT REQUEST-FOR-PROPOSAL FEATURES

1. Introduction

The chief intent of the Shuttle Processing Contract (SPC) is to consolidate the management and conduct of Shuttle launch operations at both KSC and VAFB under one contractor to improve efficiency and reduce costs. These launch operations at KSC involved thirteen different contractors, as well as NASA personnel. The Request for Proposal (RFP) includes a formulation of proposed practices that are hoped to bring about a reduction in Shuttle launch costs and an increase in the flight rate over the current Mission Model. This section extracts the salient paragraphs from the RFP that delineate these practices, and then provides some comments regarding areas that may require further definition.

2. Extracts (with page numbers in the RFP from which the paragraphs were taken)

A. SCOPE OF WORK (p. 293)

1. "This contract encompasses the overall Shuttle Processing activities at KSC and VAFB. It shall be the responsibility of the Contractor to process individual vehicle elements, to integrate those elements in preparation for launch, to perform cargo integration and validation activities with the orbiter, to operate and maintain assigned facilities and required support equipment, and to perform those tasks necessary to accomplish successful launch and post-launch activities of the Shuttle vehicles. The Contractor shall, in accordance with the terms and conditions set forth herein, manage and provide that effort necessary to accomplish the requirements of the Statements of Work attached hereto and made a part hereof, as Attachment I.*"

2. "The scope of this contract includes the effort necessary to accomplish the program milestones, mission manifests and traffic model initially depicted in RFP Exhibit 3* and typical STS processing schedules initially depicted in RFP Exhibit 4*. Revisions to these milestones, manifests, models and/or processing schedules may be made by the Government, and such revisions will be deemed to be within the scope of this contract. The Government will consider a proposed equitable adjustment to the contract for either of the following two reasons unless the contractor's actions are a significant contributing factor."

a. "The estimated cost of any single event exceeds $5 million (an event is defined as anything that delays a scheduled launch once its processing starts or as a compression of a process flow once commenced to avoid a launch delay)"
b. "The elimination of a scheduled mission within the current contract period."

"There shall be no equitable adjustment pursuant to any other provision of this contract unless the order, direction, event, or conduct described in such provision causes an increase or decrease in the estimated cost of performance of more than $5 million. The above limitation is not applicable to change orders issued to implement any facilities project estimated to cost in excess of $75,000."

*Not included here.

B. PERIOD OF PERFORMANCE (p. 61)

"The initial contract period of performance is contemplated to begin October 1, 1983, and end September 30, 1986. The contract will also contain four (4) options to extend the period of performance an additional twelve (12) years. They will consist of one (1) priced option for a period of three (3) years and three (3) unpriced options of three (3) years each for a total potential contract period of performance of fifteen (15) years."

C. TRANSITION (pp. 10, 12, and 13)

"The transition of responsibilities from the incumbent flight element hardware processing contractors will be phased into the SPC at KSC as the SPC meets certain pre-determined transition criteria. Transition is defined as the period from SPC contract start through that point where the SPC has received Government approval to assume responsibility for performing all contract requirements." (See Figure III-7.)

"Transition at VAFB can be basically described as transition by schedule or milestone event. As in the case of KSC, however, certain demonstrations of proficiency and readiness of planning will be required to facilitate judgments by the Government prior to the SPC assuming full responsibility."

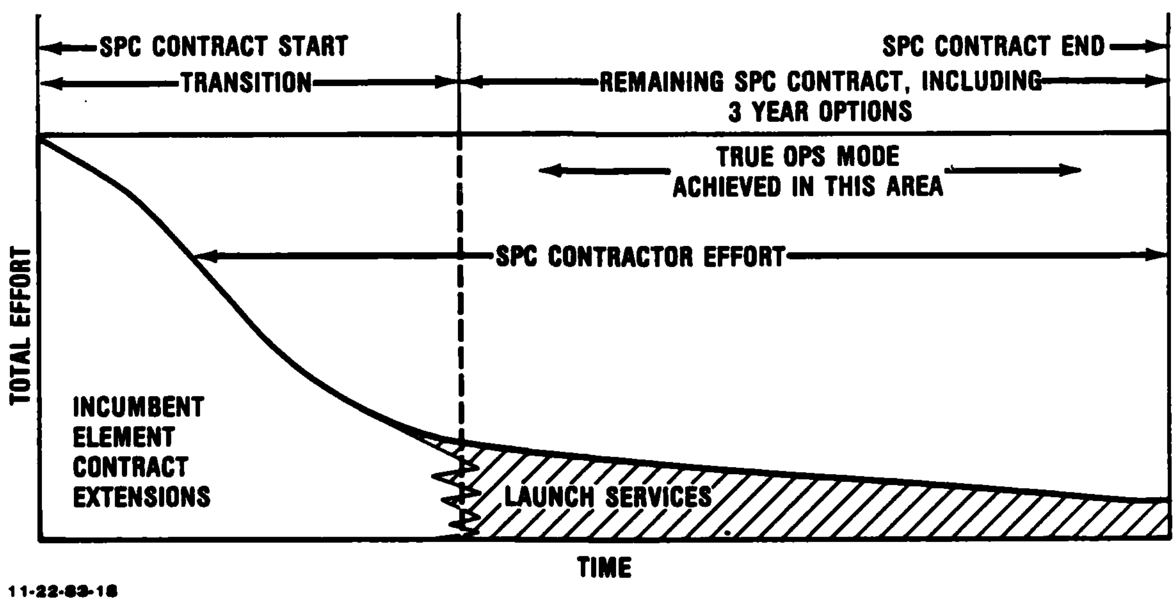

FIGURE III-7.
(Drawing & Curve Not to Scale)

"At the end of the transition period the incumbent Processing Contractor efforts will reduce to one of launch services, see Fig. III-7. In this timeframe, four basic contract areas of effort will exist: the Shuttle Processing Contract; Base Support Contracts (BOC at KSC, Host Base and Western Test Range at VLS); Incumbent Launch Services; and the continuing Flight Hardware, Development, Production and Sustaining Engineering Contracts with the original developers."

"At the beginning of the launch services effort, a scenario similar to the following is expected: the SPC is fully responsible to perform all requirements of the SPC SOW, i.e., Shuttle processing, launch, recovery, and turnaround including sustaining engineering of ground systems, support equipment and facilities. The original Flight Hardware Development Contractors are responsible through NASA Development Centers Contractors to provide Flight Hardware sustaining engineering, flight spares, and certain flight LRU Maintenance."

D. MODES OF CONTRACT (pp. 105, 106, 115)

"(1) NASA/KSC SOW -- Basic Period" (see Fig. III-8)

"During the transition period (to be proposed by the offeror and agreed upon by the parties), a Cost Plus Award Fee (CPAF) mode will be employed. The contractor's award fee will be determined at the conclusion of the transition period based on an overall assessment (macroanalysis) by senior Government management personnel of the effectiveness and timeliness of the contractor's accomplishment of the transition objectives."

"Following the transition period, a Cost Plus Incentive with Award Fee feature (CPIF/AF) mode is planned for the remainder of the basic 3-year period and for the priced option period. The maximum available incentive and/or award fee may not exceed 15%. It is expected that the predominance of the available fee would be incentive fee, although an adequate award fee pool would be established to provide for a macroanalysis by the Government of the contractor's overall performance and consideration for areas of concern that may not be sensitive to the incentive features. Award fee determinations would be made semiannually by the Government. Incentive fee would be based on the contractor's deviation from the planned number and average cost of missions to be accomplished during the period. The number of planned missions for incentive fee determination purposes would be the number of KSC missions scheduled to be accomplished after completion of transition through the remainder of the basic period, as shown in the mission model (Exhibit 3*). Target average cost per mission would be the total target estimated cost for the period, plus imputed costs allocated under the Responsibility Accounting Program (RAP)(Attachment VII)*, divided by the number of mission opportunities specified in the mission model. The target average cost per mission would not

*Not included here.

<table>
<tr><th></th><th colspan="2">BASIC 3-YR PERIOD</th><th>PRICED OPTION (3 YRS)</th></tr>
<tr><td>KSC SOW</td><td><u>TRANSITION</u>
● CPAF
● Duration to be proposed by offerer
● Separately identified--
  ● Estimated cost
  ● Award fee</td><td><u>REMAINING BASIC PERIOD</u>
● CPIF/AF
● Separately identified--
  ● Target cost
  ● Incentive Fee
    ● No. mission opportunities
    ● Tgt. cost per mission
    ● Tgt. fee per mission
    ● Shareline
  ● Award fee</td><td rowspan="2">● CPIF/AF
● Combined target cost
● Combined incentive fee with separate calculations
  ● No. mission opportunities
  ● Tgt. cost per mission
  ● Tgt. fee per mission
  ● Shareline
● Combined award fee</td></tr>
<tr><td>VAFB SOW</td><td colspan="2"><u>TRANSITION PERIOD (3 YRS)</u>
● CPAF
● Separately identified--
  ● Estimated cost
  ● Award fee</td></tr>
</table>

NOTE: Although award fee pools may be of differing orders of magnitude and exist for differing purposes between KSC and VAFB during the basic 3-yr period, it is contemplated that award fee provisions will be administered by a consolidated KSC/VAFB award fee board.

FIGURE III-8. Planned SPC contracting mode be revised for single events for which the estimated cost impact is less than $5 million as described in the proposed contract schedule."

"(2) USAF/VAFB SOW -- Basic Period"

"The 3-year basic performance period will be considered to be a transition period, and will be on a CPAF basis. Award fee determinations will be semiannually based on overall assessments (macroanalysis) by senior Government management personnel of the effectiveness and timeliness of the contractor's achievement of transition objectives."

"(3) Priced Option Period"

"The 3-year priced option period will be on a CPIF/AF basis. There will be a single incentive/award fee structure, although estimated costs, target incentive fees and earned incentive fees will be separately calculated for KSC and VAFB missions. Other provisions specified above for the CPIF/AF mode for the NASA/KSC SOW would also apply here."

E. INCENTIVE FEE (p. 1062)

"The incentive fee portion of the total potential fee is determined based on the following formula:

$$(TFM \times SM) + [(TCM-ACM) \times CS]\ SM$$

TFM = Target incentive fee per mission

SM = Number of missions successfully accomplished (the definition of a successful mission is presented below).

TCM = Target average cost per mission

$$= \frac{\text{Estimated contract cost for period + RAP}}{\text{Mission opportunities (per mission manifest)}}$$

ACM = Actual average cost per successful mission

$$= \frac{\text{Actual contract cost for period + RAP}}{\text{Number of successful missions}}$$

CS = Contractor's share of variances from target cost.

NOTE: Except as provided in the General Provisions, TCM and ACM for each of the Statements of Work (KSC and VAFB) will include all elements of cost pertaining to the respective SOWs."

"The Government will define parameters for a successful mission prior to initiation of each mission. Normally, a successful mission

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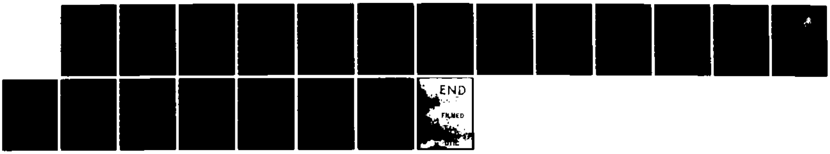

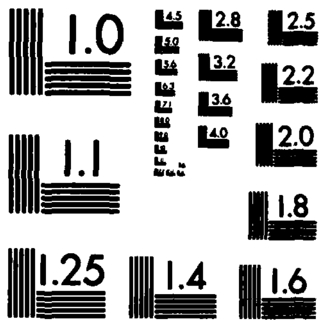

MICROCOPY RESOLUTION TEST CHART
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will be defined as one which results in (i) safe launch, and recovery of the crew, Orbiter, and SRB's; and (ii) accomplishment of primary mission objectives, as defined in JSC Flight Requirements Document."

F. AWARD FEE (p. 1058)

"The following are examples of the type of subjective criteria that will be considered during the CPIF/AF period in performing the macroanalyses of the contractor's performance for purposes of award fee determination. (Appropriate criteria will be established for the transition period emphasizing timely and effective accomplishment of transition activities and mission success.):

a. "The extent to which a proper balance has been maintained across all elements of the contract.
b. "The avoidance of marginal performance in areas which could severely impact future program accomplishments or result in work stoppages.
c. "Events which significantly impact other centers and/or contractors.
d. "Synergism with other program elements.
e. "Contributions to solving program problems and achievement of Government goals.
f. "Safety record and overall performance of hazardous operations."

3. Comments

a. Uncertainties for the Contracting Agency

(1) Incentive fee for an extra mission. The first term in the incentive fee formula (TFM x SM) appears to be intended to specify a reward for each mission success; it does not, however (see below), represent the incentive to produce one more successful mission beyond the number projected by the Mission Model in the period. The second term (TCM-ACM) x CS x SM defines the contractor's share (CS) of the average cost reduction (TCM-ACM) for the successful missions in the period; the use in the formula of the target average cost per mission (TCM), derived from the projected number of missions (MM) rather than the actual number of missions (SM), contains an implicit incentive for additional missions beyond the mission model. None of the parameters in the formula is quantified in the RFP, but the analysis below may indicate the probable range of values. At this point, suffice it to say that CS must be less than one or the contracting agency would realize

no cost reduction from the initial estimates for as long as that value was fixed (the life of the basic contract and the priced option?).

The incentive fee (IF) formula can be regrouped and, making use of the definition that ACM equals the actual cost for the period (ACP) divided by SM (neglecting RAP*), becomes

$$IF = SM(TFM + CS \times TCM) - CS \times ACP \quad .$$

<u>If one more successful flight than the number in the mission model can be accomplished without increasing the total actual cost for the period</u> (i.e., without changing the staffing level), then the incentive fee for that one extra flight, $\delta(IF)/\delta(SM)$, is

$$\delta(IF)/\delta(SM) = TFM + CS \times TCM \quad ,$$

which can be considerably greater than the target incentive fee per mission. For example, if TFM = \$2M, if CS = 0.2, and if TCM = \$20M, then the incentive fee for one extra mission would be three times the target incentive fee per mission, barring an upper limit on fee.

However, the incentive fee equation can be rewritten with a minimum of changes to overcome this deficiency while preserving the original structure of the fee definition. The target average cost per mission (TCM) can be based on the number of successful missions rather than the number of missions in the mission model (MM) and would then be derived (neglecting RAP) from an estimated contract, or target, cost for the period (TCP), i.e.,

$$TCM = TCP/SM$$

Replacing (TCM x SM) with TCP in the incentive fee formula gives

$$IF = TFM \times SM + (TCP-ACP) \times CS$$

*Responsibility Accounting Program: includes cost of services provided to SPC by others, normally small in comparison with SPC costs.

so the incentive fee for one extra flight becomes (for constant ACP) simply, and more appropriately,

$$\delta(IF)/\delta(SM) = TFM$$

(2) Number of missions to maximize fee. The total fee (TF) equals IF plus the award fee (AF) but may not exceed a cap of 15 percent of the estimated target cost for the period, TCP, per NASA, 1983c. The resulting inequality that represents the limit on total fee is (reverting to the incentive-fee definition in the RFP):

$$TF = (TFM \times SM) + [(TCM-ACM) \times CS] \times SM + AF \leq 0.15 \times TCP \quad .$$

As TCP is equal to TCM x MM and ACP is equal to ACM x SM (both as defined in the RFP), the inequality can be rewritten as

$$SM \times (TFM + CS \times TCM) - CS \times ACP + AF \leq 0.15 \times TCM \times MM$$

From this inequality can be derived the number of successful missions (SMX) in a period beyond which the contractor can gain no additional fee

$$SMX = \left[\frac{0.15 \times TCM}{(TFM + CS \times TCM)}\right] \times MM + \left[\frac{(CS \times ACP - AF)}{(TFM + CS \times TCM)}\right]$$

For assumed plausible baseline values of the parameters

CS = 0.2, i.e., the SPC keeps 20% of the reduction he achieves
ACP = \$100M per 6-month period
AF = \$1M per 6-month period
TFM = \$2M per successful mission
TCM = \$20M per mission

which are based on the estimate in the RFP (p. 104) for the annual total staffing costs of \$219.45M at the beginning of the contract (the year of the dollars is not specified, but all the assumed dollar values can be scaled by any common factor, e.g., all doubled, without changing the results), the number of successful missions in a period beyond which the contractor can earn no more fee is

$$SMX = 0.5 \times MM + 3.167 \quad .$$

This expression says that, for the assumed (fixed) values of the parameters, SMX will be less than MM for all values of MM greater than 6-1/3. In other words, in general for certain fixed values of the parameters in the incentive-fee formula, the contractor will have earned his maximum fee for a number of successful missions that is less than the number in the mission model--a situation that is clearly undesirable. This situation can be rectified by allowing the parameters in the SMX expression to change with MM for each period.

To determine the desired variation of the parameters, set SMX equal to MM in the SMX equation above and solve for the value of each parameter. The resulting expressions for the parameters are the following

$$CS = \frac{(0.15 \times TCM - TFM) \times MM - AF}{TCM \times MM - ACP}$$

$$ACP = \frac{[TFM + (CS-0.15) \times TCM] \times MM + AF}{CS}$$

$$AF = [TFM + (CS-0.15) \times TCM] \times MM - CS \times ACP$$

$$TFM = \frac{(CS \times ACP - AF)}{MM} - (CS - 0.15) \times TCM$$

$$TCM = \frac{(CS \times ACP - AF)}{MM \times (CS-0.15)} - \frac{TFM}{(CS-0.15)} \quad .$$

Actually, ACP (the total actual cost for the period) will be what it comes out to be, and the dependences of SMX on TCM and AF are very weak, so the critical controllable and controlling parameters are CS and TFM. For values of either held fixed at the baseline value, the other should vary with flight rate to make achievement of the maximum fee coincide with achievement of the desired number of flights, as follows:

	MM =	8	10	12	(per 6-mo. period)
parameter held constant					
CS = 0.2:	TFM =	1.375	0.900	0.583	($M)
TFM = 2.0:	CS =	0.117	0.090	0.079	(fraction)

So, while the variable values of CS and TFM shown above are somewhat less than the baseline values assumed, they are not unreasonable, and the proper control of the fee can be obtained if periodic contract adjustments can be made.

The provisions for contract adjustments outlined in the "Scope of Work," paragraph 2, are of particular interest as they reflect an approach adopted by the Government to control costs. The position of the Government is essentially this: The Contractor should be able to manage his manpower (the principal element affecting costs) in such a manner as to decrease effort in selected areas, delay or postpone activities, or adopt other measures to offset any increased effort required in other areas to avoid a launch delay--at least to the extent of a $5 million single event. For example, should two events develop each of which is estimated to cost $4 million, the Contractor is expected to offset the estimated $8 million increase by the means outlined above.

(In principle, this approach appears sound but there undoubtedly will be instances and circumstances when the Contractor and the Government will disagree. In the example just described, for instance, it might be argued by the Contractor that the two events impacting the launch date are really two components of a single more comprehensive event in which case he would expect an equitable adjustment to be negotiated as described in the "Scope of Work," paragraph 2.)

It is through the adjustment methodology outlined above that NASA hopes to be able to modify the contract to account for conditions that will vary with time, such as the redefinition of the incentive-fee parameters, and for any other required changes in control that will emerge as Shuttle processing experience is acquired.

b. <u>Uncertainties for the Contractor</u>. Modifications to the Shuttle launch system to reduce turnaround time and servicing costs fall into four categories of actions:

1. Streamline and/or abridge procedures,
2. Eliminate delays in obtaining replacement parts and expendables,
3. Improve and/or augment facility elements to facilitate or expedite servicing, and
4. Modify the Orbiter, SRB, and/or ET to improve serviceability.

The SPC is given unilateral control over only the first two; the RFP (pp. 62A, 420, and 421) acknowledges the possibility that the SPC will need and should propose changes for the last two, but the implementation is left to the contracting agency. The SPC is expected to work for rewards from providing products (improved Shuttle launch rate and economy) that are, however, critically dependent on the throughput capacities and work accessibilities of the facilities furnished by the contracting agency, and limits set by choking or servicing inefficiency of elements may be relieved only through the delay-fraught and uncertain process of obtaining approval from OMB and Congress for facility-acquisition funds.

It seems somewhat risky for a profit-making company to rely for its profits on the marketing and price-setting abilities of a non-profit organization (NASA/USAF, i.e., the U.S. Government), especially one subject to the decision process of the U.S. Congress. Suppose, for example, that there were no payload demand for that extra flight that the SPC might be motivated to squeeze into a semiannual period for increased fee (within fee limits); or suppose that the price set by the pricing policy of NASA/USAF were not as competitive with alternative launch systems as the SPC might be able to make it, and the prospective customers assumed in the Mission Model defect to other launchers; or if a payload slips and impacts the schedule; or if a payload needs services that extend the timeline. (About one-third of the Shuttle flights in the Mission Model are to carry non-government, ELV-compatible payloads.) Such eventualities may need to be considered in the periodic reassessment of the contract.

IV. POTENTIAL IMPACT OF NEW SPACE INITIATIVES

A. SPACE STATION POSSIBILITIES

The idea of a manned orbital facility of long duration as an essential element in the development of the nation's space capability has been put forth by NASA since the beginning of the civilian space program in 1958. The current rationale offered for a space station is twofold: (1) it can serve as a research and development facility in space for exploring scientific issues and developing unique space technologies and (2) it can be an operations center for on-orbit assembly, on-orbit storage and as a deployment platform for orbital transfer vehicles (OTVs). It is this latter potential use that may be of interest to DoD mission planners. The existence of a reusable space-based OTV and/or a manned sortie OTV would broaden the possible missions destined for geostationary and high energy orbits.

A brief discussion of the utilization of a manned platform in space for servicing and logistics missions appears in MDAC, 1982 (one of several NASA-contracted studies). It is stated that a Manned Space Platform could support a space-based OTV having increased performance; the space-based OTV need not be designed for the earth launch environment and thus could be designed to a lighter weight. The reduced propellant need would also require fewer logistics flights. Figure IV-1 taken from the reference illustrates the relative propellant delivery needed to LEO for a geosynchronous mission as a function of stage mass fraction. A detailed design of a ground-based cryogenic OTV studied by MDAC yielded a mass fraction, λ', of 0.89, whereas a similar OTV based in space had a mass fraction, λ', of 0.92, thus allowing a 30% reduction in fuel transportation costs to LEO. The higher mass fraction was primarily due to reduced structural weight. Detailed studies are required, however, to substantiate these results. Such studies are currently planned by NASA as part of the continuing effort on justification arguments for a Space Station program.

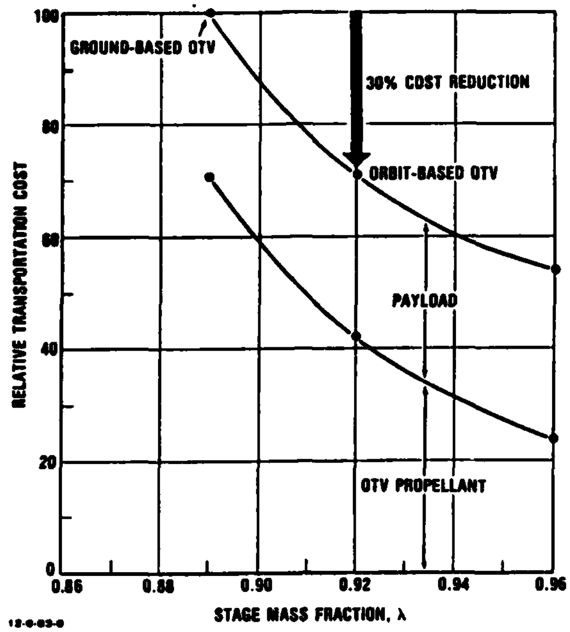

FIGURE IV-1. Transportation Cost Sensitivity--GEO (from MDAC, 1982)

The reference also describes a scenario of a manned platform serving the needs of a space plane--a small reusable manned vehicle for sortie missions to other orbits. The manned platform could be used for vehicle storage, crew training, and checkout prior to launch. It is argued that one aspect of this type of mission is the reduced time response to reach a high orbit such as geostationary. Another response time advantage of orbit basing the space plane (or OTV) is that only the transfer vehicle has to be kept in a state of readiness to launch compared to the entire vehicle for a ground-based concept.

B. TETHERED SATELLITES

According to PS, 1983, tethered satellites have been utilized to augment the effectiveness of surveillance satellites for some time. The reference discusses the deployment of "three small sub-satellites at the ends of 10-mile-long tethers" trailing "the U.S. satellite, code-named

White Cloud." Tethered satellites for scientific purposes were discussed in IDA, 1978. Currently, as reported in NSO, 1983, NASA is working with Italy on a joint project that would employ tethered satellites for various scientific purposes. Samples of the proposed uses are illustrated in Fig. IV-2 (NSO, 1983). Some experiments would require dragging a small satellite through the Earth's upper atmosphere at the end of a 100-km (approximately 60-mile) tether (IDA, 1978 and PS, 1983). The satellite weight can be as great as 500 kg (~1100 lb). The U.S.-Italy joint venture is scheduled for a first flight in 1987. This development should be of interest to the DoD inasmuch as the Space Test Program may find this technique suitable for certain experiments that might otherwise require separately launched satellites.

C. MANEUVERING SYSTEMS

IDA, 1977 contains a discussion of the potential use of manned and unmanned (remotely controlled) maneuvering units or spacecraft for supporting the in-orbit servicing of satellites. Since that time NASA has developed a Manned Maneuvering Unit (MMU) that will attempt in 1984 to rendezvous with the disabled Solar Maximum Mission satellite, and stabilize it so that the Shuttle Remote Manipulator System arm can retrieve it into the Shuttle Cargo Bay for in-orbit repairs, if that is feasible, or for a return to earth.

NASA (NASA, 1983d) plans to develop an Orbital Maneuvering Vehicle (OMV) for various applications as illustrated in Fig. IV-3. (This development was identified previously as a Teleoperator Maneuvering System (TMS)). The OMV can be deployed from the Shuttle by itself to deliver or retrieve spacecraft at orbital altitudes up to 1100 nmi or used in conjunction with other upper stages to deliver spacecraft to higher orbits. The OMV would result in a significant increase in Shuttle performance, as shown in Fig. IV-4.

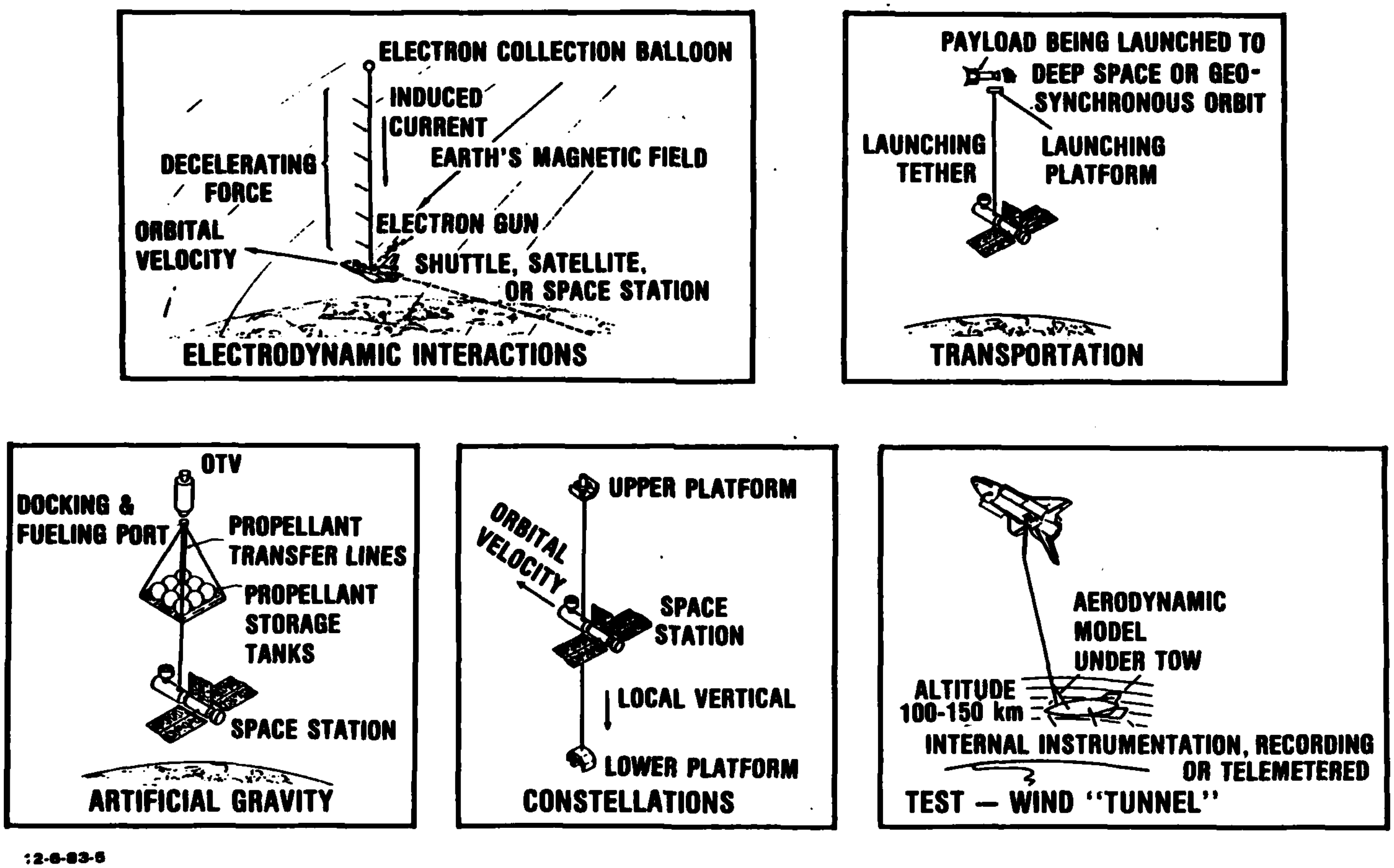

FIGURE IV-2. Tether Applications in Space (from NSO, 1983)

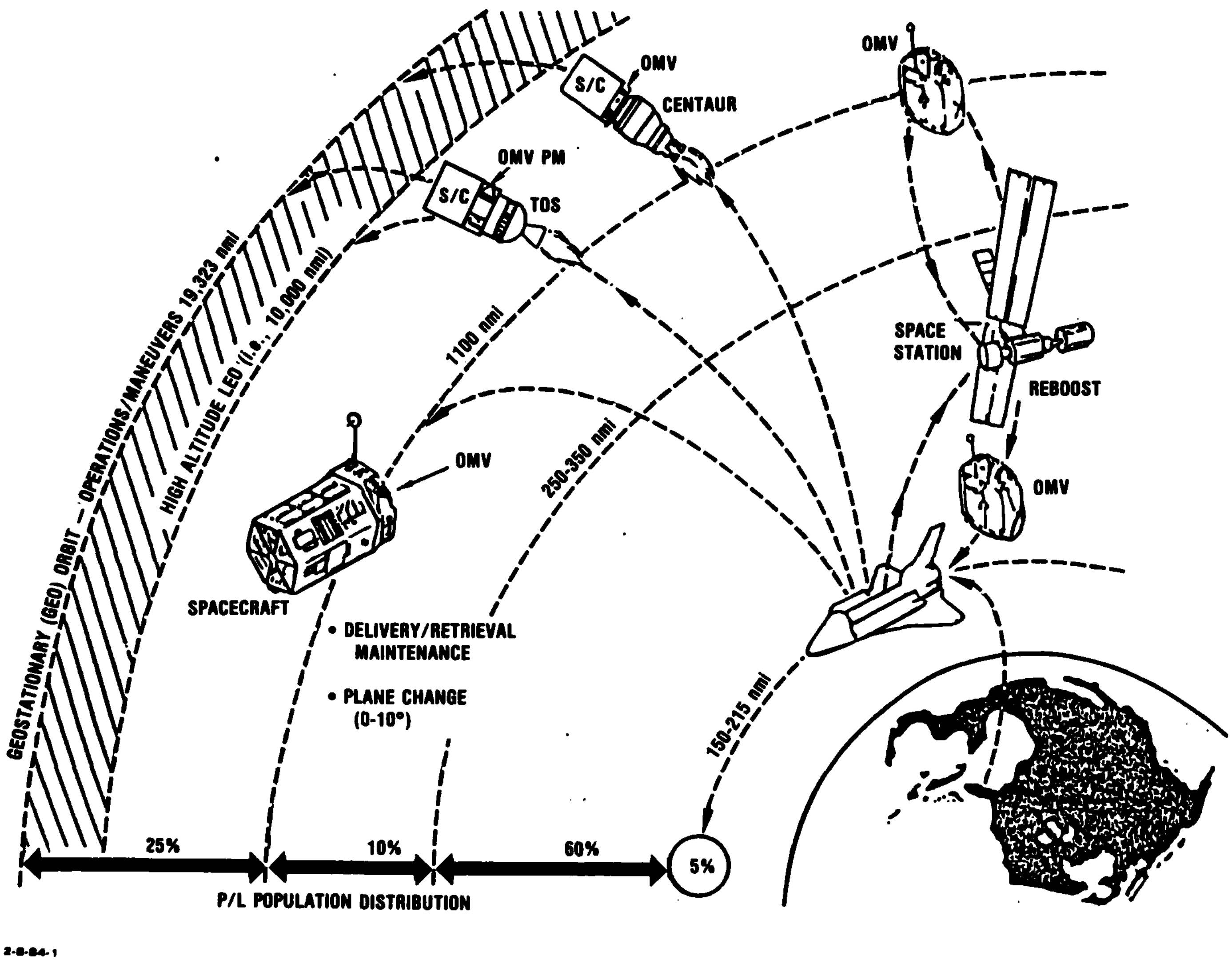

FIGURE IV-3. OMV Mission Applications (from NASA, 1983d)

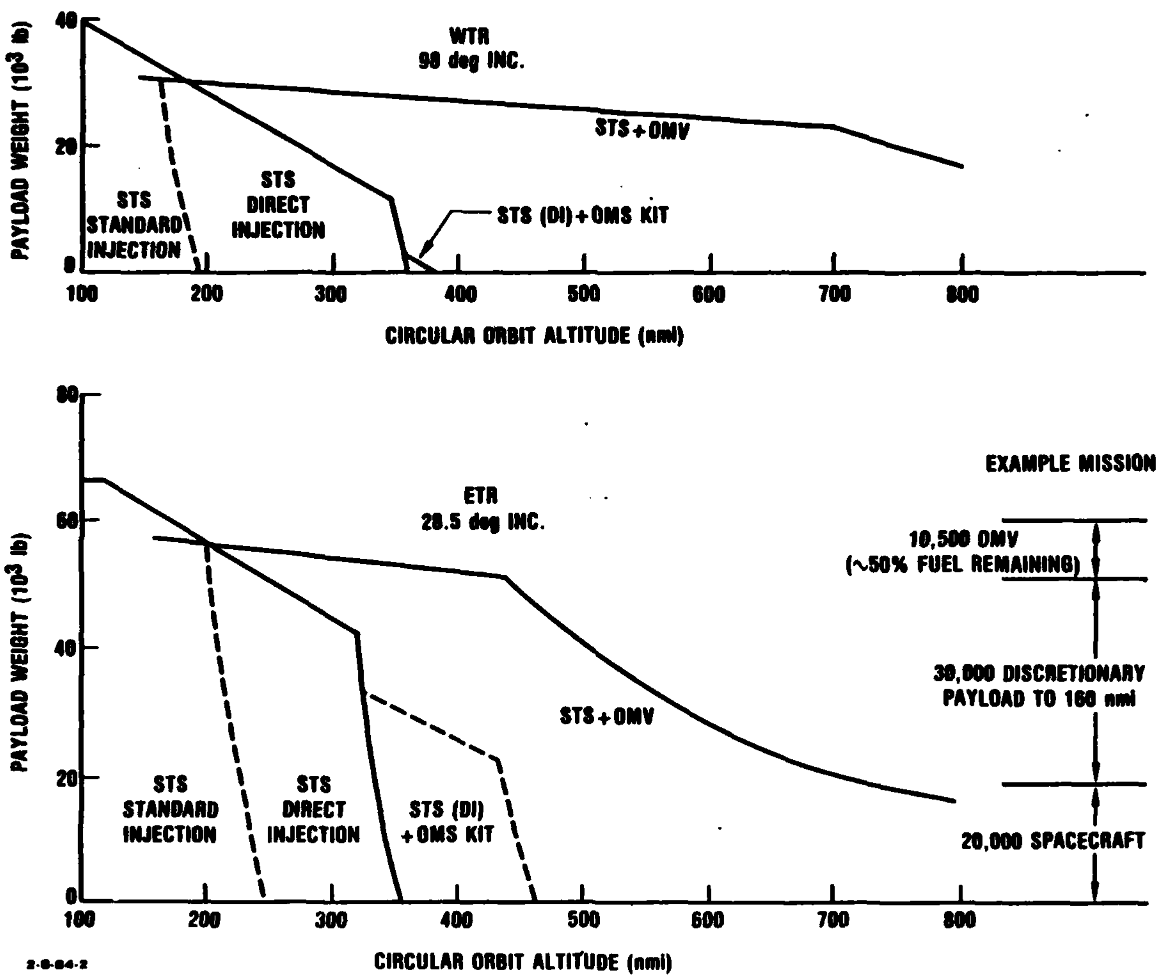

FIGURE IV-4. Performance Capabilities of Shuttle, Shuttle + OMS and Shuttle + OMV (from NASA, 1983d)

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* No classified material from the classified references on the above list was used during the preparation of this document.

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APPENDIX

TASK ORDER T-3-182

OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301

RESEARCH AND ENGINEERING

22 March 1983

TASK ORDER
NO. MDA903 79 C 0018: T-3-182

TITLE: Advanced Space Systems Analysis for Enhanced Operational Utility

1. This task order is for work to be performed by the Institute for Defense Analyses (IDA) for the Deputy Under Secretary of Defense (Strategic and Theater Nuclear Forces), OUSDRE.

2. BACKGROUND:

With the completion of the Shuttle's flight tests, the Space Transportation System (STS) and military space systems that interact with it enter a new operational era. The new capabilities of the STS, e.g., relaxed weight and volume constraints, manned tending, and spacecraft recovery, provide opportunities for the military to deploy advanced space systems that will have enhanced operational utility to military missions. The new capabilities will convey advantages only up to certain new limitations, however, that will apply, for example, in flexibility, in responsiveness, in survivability, or in cost. Some of the constraints imposed on advanced military systems by STS limitations may be subject to relaxation by improvements, or even supplements, to the STS. Advancement in military space systems will be stimulated by the STS, but in addition will suggest directions for augmentation of the STS for further enhancements in operational utility.

3. OBJECTIVE:

The general objective of this task is to analyze space transportation needs of advanced military space systems with a view to identifying requirements for augmentation of STS capabilities with improvements in performance or addition of complementary systems.

4. SPECIFIC TASKS:

The task is defined in terms of the following subtasks:

a. Space Transportation Supplements. Identify and characterize supplementary systems to enhance the operational utility of military space systems with particular emphasis on survivability and endurance requirements. As time permits, identify and quantify improvements to the STS itself for like goals.

b. Space Transportation Costs. Review and critique NASA and USAF operational concepts and associated projections of launch, payload integration, and other launch related program costs (excluding payload costs) and identify and perform evaluations of means to reduce such costs. Emphasis will be placed on Vandenberg Shuttle operations under low launch rate scenarios and ways to reduce the costs associated with the current DoD payload integration process.

c. Impact of Space Station Operations. Identify and analyze the prospective impact on space transportation systems operations concepts, requirements and costs, of the availability of a manned space station as a space transportation node.

d. Commercialization of Expendable Launch Vehicles. Identify and analyze the impact of prospective commercialization of expendable launch vehicles on Space Shuttle operations including fleet size and operations costs considerations.

These subtasks and, as mutually agreed, additional efforts of a time-urgent and relevant nature, will be pursued as resources permit.

5. SCHEDULE:

This effort will begin 1 October 1982. A draft final report will be delivered by 30 September 1983*, with final report delivered three months thereafter. Informal monthly progress reports will be provided, as will briefings on significant issues, as appropriate.

6. FUNDING:

$200,000 of FY 83 funds are authorized for this task. Total costs include all costs for computer, consultants, travel, subcontractual and other support which may be required for this task.

7. TECHNICAL COGNIZANCE:

Technical cognizance for this task is assigned to the Director (Offensive and Space Systems), DUSD(S&TNF).

8. SPECIFIC ADMINISTRATIVE INSTRUCTIONS:

a. If at any time during the course of this task, IDA identifies the need for changes in this task, such as additional resources, schedule modification, changes to emphasis of effort or scope, etc., as set forth in the above paragraphs, a report with appropriate recommendations, will be submitted in accordance with the terms of the IDA/WSEG Memorandum of Understanding of 12 March 1975 (and its successor) as applicable to the Director, DOD-IDA Management Office, OUSDRE, with a copy to the sponsor or his project officer, as appropriate. Changes in this task will be made only with the approval of appropriate cognizant DoD officials.

*Changed to 30 November 1983 by task order amendment.

b. This task will be conducted under Industrial Security Procedures in the IDA area. If certain portions of the task require the use of sensitive information which must be controlled under military security, the DOD-IDA Management Office will provide supervised working areas in which work will be performed under military security control.

c. A "need to know" is hereby established in connection with this task and access to classified documents and publications and security clearances necessary to complete the task will be obtained through the DOD-IDA Management Office unless otherwise instructed. Report distribution and control will be determined by the Director (Offensive and Space Systems), DUSD(S&TNF).

James B Statler
JAMES B. STATLER
Colonel USA
Director
DOD-IDA Management Office

ACCEPTED: ______________________
ALEXANDER H. FLAX
for President, Institute for Defense Analyses

DATE: 3/24/83

END

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